PLACING US AIR FORCE INFORMATION TECHNOLOGY INVESTMENT UNDER THE "NANOSCOPE"

A CLEAR VISION OF NANOTECHNOLOGY'S IMPACT ON COMPUTING IN 2030

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ABSTRACT

The US Air Force (USAF) faces mounting fiscal challenges due to continuing Global War on Terror requirements, pressing system recapitalization needs and competing demands from other federal agencies. To properly invest its scarce resources toward mission success, the USAF should strive to anticipate the future of technology. When two or more technology areas converge, paradigm shifts often occur that alter established boundaries enabling revolutionary changes. For example, the merging of information technology (IT) and biotechnology has spawned "bioinformatics" and a genomics revolution. This study explores the revolutionary change anticipated with the convergence of nanotechnology and IT as well as its effect on the USAF.

The emerging revolution of nanotechnology is expected to stimulate enormous improvements in IT capabilities, far beyond those possible with silicon-based electronics. This research paper uses the Delphi method, a technology forecasting approach that combines the opinions of a panel of subject-matter experts, to determine the most probable future state of nanotechnology in the realm of IT in the year 2030. The intent is to educate key USAF decision makers and planners on this critical topic while advancing the technical community's understanding based on the elite panelists assembled.

The central question of this research is: Where should the USAF invest in nanoscience and nanotechnology to best enable IT capabilities that perform its mission in the year 2030? Eleven panelists were asked a variety of questions to gather relevant information to reach the desired level of insight on this central topic. The final study results support the following thesis: To best enable USAF IT capabilities to meet US national security challenges in 2030, the service should fund nanotechnology research

and development of sensor systems and security capabilities while simultaneously investing its time promoting long-term, fundamental research and environmental conditions to grow a technology workforce.

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SECTION 1: INTRODUCTION

1.1. Issue Background and Significance

The thought of molecular science and its derivative technologies inspires varied reactions from enthusiasm and hope to panic and insecurity. Negative emotions frequently result from reservations about the uncertain consequences of radical change. The world has never been the same since science harnessed the power of the atom in the form of a doomsday weapon in the 1940s. In the 21st century, scientists seek to unlock a different type of atomic power—one focused on construction versus destruction. This new endeavor, termed nanotechnology, offers fundamentally new approaches to material property enhancement and synthesis with unlimited potential.

There has been considerable debate over the proper meaning of the term nanotechnology; however, within the US, the National Nanotechnology Initiative (NNI) description is commonly regarded as the authoritative definition. The US government established the NNI in 2000 to coordinate federal interagency efforts in nanotechnology science and technology (S&T) (National Research Council (NRC), 2006, 1). Per the NNI, **nanotechnology** is defined as "the understanding and control of matter at dimensions of roughly 1 to 100 nanometers, where unique phenomena enable novel applications" (NNI, 2006, np).

Dr. Ottilia Saxl, founder and Chief Executive Officer (CEO) of the Institute of Nanotechnology, wrote, "The growth of civilisation [sic] has been founded on the innovative development and use of materials, from bronze to glass to tin to concrete to gunpowder – to name only a few" (Saxl, 2005, 7). Nanotechnology seeks to better comprehend and control the unique material attributes of matter at the nanometer length

scale, or nanoscale, to harness useful macroscopic properties and even design completely new materials and devices. Nanotechnology promises to create a new generation of information technology (IT) devices that will enable computing and networking capabilities in unimaginable ways. Dr. James Ellenbogen, Senior Principal Scientist of the Nanosystems Group at Mitre Corporation, stated, "[Nanotechnology] will cause people to rethink the potential of IT. When you make something a thousand times smaller, you cross the transition line where things that formerly were impossible suddenly become obvious" (Jackson, 2003, 1).

For the average individual, the future potential of IT-focused nanotechnology is hard to fathom as many traditional boundaries are eliminated or simply not important at the nanoscale. Expected benefits include computers that are smaller, more portable, cost less, consume less power and are far more capable. The capability to manipulate individual atoms and molecules is expected to build new kinds of quantum electronic devices that will revolutionize the 21st century in much the same way that the invention of the computer led to the Information Age (Wilson et al, 2002, 189-90). This paper assumes the reader is knowledgeable on the subjects of nanotechnology and IT. If not, Appendix 11 contains contextual information on these technical fields to establish the necessary background for this research.

The USAF heavily relies on IT systems to execute its technology-oriented mission and, as a result, must understand and seek to shape the potential impacts of nanotechnology. As declared in Air Force Doctrine Document (AFDD) 1, "Dominating the information spectrum is as critical to conflict now as controlling air and space, or as occupying land was in the past, and is seen as an indispensable and synergistic

component of air and space power" (AFDD 1, 2003, 78). This realization has been a driving force which has led to the recent stand-up of a USAF Cyberspace Command. Mr. John Gilligan, USAF Chief Information Officer, acknowledges the USAF increasingly depends on commercial IT technologies and develops custom technology solutions only when those necessary are not available on the commercial market (Keller and Wilson, 2004, 35).

The paper seeks to forecast the most probable future state of nanotechnology in the realm of IT in the year 2030. To best enable USAF IT capabilities to meet US national security challenges in 2030, the service should fund nanotechnology research and development (R&D) of sensor systems and security capabilities while simultaneously investing its time promoting long-term, fundamental research and environmental conditions to grow a technology workforce. This position was developed through the successful implementation of the Delphi technology forecasting methodology.

1.2. Technology Forecasting and the Delphi Method

Technology forecasting is an art more than a science. It includes all efforts to project technological capabilities and predict the discovery and spread of technological improvements (Ascher, 1978, 165). The benefit of a technology forecast lies in its ability to improve the quality of decision making and not whether or not it eventually comes true (Martino, 1993, 15). Most government and corporate strategic planning projections don't exceed 15 years. IT forecasts are even less aggressive due to the dynamic nature of the industry. In order to put together a credible outlook for the year 2030, the knowledge and

insight of well-established, subject-matter experts (SME) are needed to assess the complexities, interdependencies and other nuanced aspects of this research topic.

Top professionals in the fields of nano and computer S&T from a cross-section of government, industry and academia were identified and invited to participate in this research project. The Delphi method was selected as the best means for systematically collecting and synthesizing the informed judgments and insights of the chosen experts to discover both points of consensus and disagreement about the future. This method, first introduced by RAND Corporation, allows structured interchanges among a geographically dispersed group of experts via electronic correspondence (Ascher, 1978, 185). The anonymity and feedback facilitated by this method promotes calm and objective debate to explore issues requiring judgment (Gordon, 2003, 9).

Successful implementation of the Delphi method relies heavily on the quality of the selected panel members (Gordon, 2003, 7). A thorough examination of published, peer-reviewed journals and the Internet was conducted to locate acknowledged experts in the subject fields. Each expert was initially contacted via e-mail to determine the individual's willingness to participate. The e-mail provided a brief introduction to the research initiative and solicited the name of an appropriate point of contact to schedule a 30-minute appointment over the telephone. The resulting conference call provided the venue to accomplish personal introductions and better describe the research project along with the desired SME support. The objective of the phone call was to invite the SME to take part in the research project and ideally gain a verbal commitment of participation. As a follow-up, a formal letter was mailed to each confirmed participant acknowledging

the invitation and thanking them for their willingness to support this significant, USAF research initiative. A sample copy of the invitation letter is located in Appendix 6.

A total of 42, prominent SMEs in nanotechnology and IT were contacted via e-mail for this research project. In the end, 11 individuals agreed to take part in the study. While most studies use panels of 15 to 35 people (Gordon, 2003, 8), 11 was assessed as more than sufficient based on the time and resources available. Two, additional authorities on these technologies were enlisted to act as advisors to help phrase and qualify the research questions to prevent any flaws or potential misinterpretations by the panelists due to word choice. Counting the two advisors, the final panel acceptance rate was 31 percent as compared the anticipated 35 to 75 percent referenced in the literature (Gordon, 2003, 8). A complete list of all the study participants, to include their photos and biographies, has been provided in Appendix 4.

Another key element to the success of the Delphi method was the formation of the questions posed to the panelists in the form of questionnaires. Considerable thought was put in to the number, substance and relevance of these questions. Background research was conducted to narrow in on those issues of primary interest in getting to the heart of the central research topic. The decided-upon format for the study required each participant to answer two, sequential rounds of questions. While a third-round questionnaire would have further crystallized panel opinions, time constraints caused by panelist schedule demands and research program scope restricted the effort to two questionnaires. The first was distributed on 29 November 2006; the second, on 10 January 2007. The two questionnaires were prepared to include clear instructions outlining the process and objectives. For each questionnaire, the panelists were given

three weeks to craft their responses. This was in line with the recommended turnaround time of weeks from the literature (Gordon, 2003, 9). The final draft version of each questionnaire was sent to the two, Delphi panel advisors. As it ended up, each advisor qualified the prepared questions for one of the two questionnaires prior to it being released to the panelists. The final versions of Questionnaire #1 and #2 can be found in Appendix 1 and 2 respectively.

Applying the Delphi method, the narrative responses to the initial questionnaire were examined, subsequently collated and then incorporated with minimal editing into the second-round questionnaire. This feedback of prior-round information into the next round allowed all participants the opportunity to reassess their earlier views in light of the other panel members' answers. The first-round responses were also used to better focus the questions in the second questionnaire. Throughout the process, the participants' answers were not attributed to them by name to encourage free and open debate. This technique succeeded in helping to form candid, aggregate positions on the revolutionary change anticipated with the convergence of nanotechnology and IT.

The results represent the synthesis of judgments of the particular group and do not predict the outlook of a larger population or another Delphi panel (Gordon, 2003, 5). The significance of the results is in the ideas the panel generates both the ones that incited debate and others that lead to agreement (Gordon, 2003, 5). The overall success of this method relies heavily on the participation and cooperation of the panelists. Experience with the Delphi method indicates a participant response rate from 40 to 75 percent should be anticipated (Gordon, 2003, 9). It is noteworthy that all 11 panelists in this study completed both questionnaires. The 100 percent response rate served to compensate for

the smaller panel size. This accomplishment was due in large part to clear and open communications with the individual panelists throughout the process.

A data table, in some cases two, has been created for each topic to organize and analyze the various panel responses. These data tables are located in Appendix 7. All responses for each topic were ranked using a simple scoring system to reveal those answers that produced the highest level of consensus among the panel. A response's overall score was calculated by adding one point for every panelist who concurred with it and subtracting a point for each one that disagreed. No scoring adjustments were made if a panel member did not take a position on the response. Therefore, the higher the overall score, the greater the level of consensus on a particular response. While there is information to be gained from the areas of disagreement, this report will focus on the responses with the highest level of consensus to develop a better understanding of the expected future. A compilation of all the panelists' answers has been assembled and formatted into an intelligible product located in Appendix 3. This unfiltered record is an extremely valuable document based on the top-notch participants in the study.

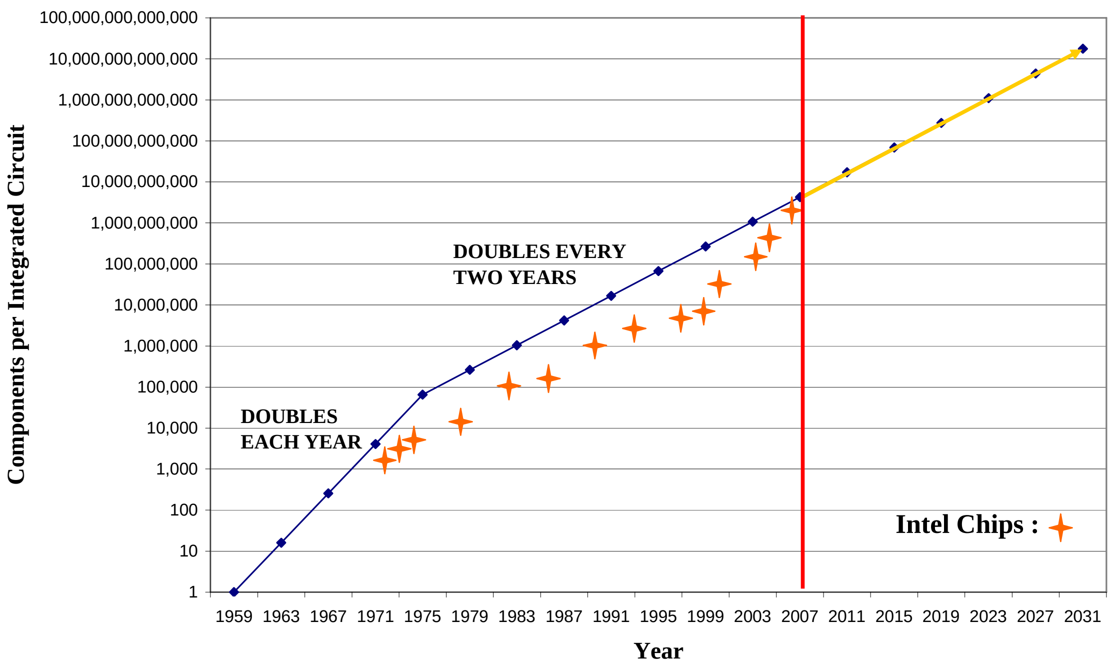
SECTION 2: NANOTECHNOLOGY-DRIVEN INFORMATION TECHNOLOGY

2.1. Moore's Law—the Pace of Change and Barriers to Overcome

The International Technology Roadmap for Semiconductors (ITRS) is the semiconductor industry's common reference document that anticipates the major developments in the global, integrated circuit (IC) market 15 years into the future. The ITRS is produced by an international group of experts through a consensus-building process. The most current Roadmap, the 2005 full revision with its companion 2006

update, extends out to the year 2020. While its targets provide useful guidelines for predicting future IT capabilities, the ITRS is not a technology forecasting exercise but rather a method to indicate where research should focus to continue to advance Moore's Law (International Roadmap Committee (IRC), 2005, 4).

Figure 2.1 Moore's Law (Extrapolated to 2031)



Moore's Law states IC density, or number of transistors on a chip, doubles every 24 months (IRC, 2005, 1). Moore's Law was never considered a law of physics, but rather a rule of thumb about how complex ICs would become. The IT industry has adopted the trend in order to plan and focus its capital investments on key areas that promote the constant evolution of silicon semiconductor technology. A complete overview of Moore's Law has been included in Appendix 9 to educate the reader on the scaling trend that is the driving force for the current pace of change in IT. Figure 2.1 provides a graphical representation of Moore's Law from its origin in 1965 and is linearly

extrapolated out to 2031. As the world's largest chip maker, Intel Corporation transistors per production chip data has been plotted on Figure 2.1 to show how closely Moore's Law has tracked with reality.

For 42 years, scaling has been the organizing theory for the progress of the semiconductor industry. It has created a structure for continued process improvement and helped unite the entire industry around design and manufacturing. The impact of transistor miniaturization is improved performance, or computational speed, because electrons do not have to travel as far. The ability to pack more and more transistors and other circuitry onto chips has also steadily increased their functionality.

The **end of Moore's Law** has been erroneously speculated many times over the past few decades. In 1978 and again in 1988, International Business Machines Corporation (IBM) scientists predicted Moore's Law had only 10 years left. Dr. Gordon Moore, the originator of Moore's Law, himself thought his law would end at the 250 nanometer (nm) manufacturing process, a milestone the semiconductor industry passed in 1997 (Kanellos, 2005, 4). So, how far can the transistor shrink? The only true boundaries to innovation are the absolute limits of physical science—quantum and thermal restrictions of complexity. The regular doubling of IC density does mean that these absolute boundaries are approaching rapidly.

Moore's Law cannot continue forever. The sustained increase in the number of transistors with the corresponding decrease in size is pushing the semiconductor industry toward the dimension of a single atom—.3 nm in diameter for silicon and .2 nm in diameter for carbon. This is the ultimate scaling limit since transistors and wires cannot be made smaller than an atom and solids cannot be produced out of hydrogen.

Manufacturing process technology is now at the point where some features/structures of chips, such as the gate oxide layers, are already only a few atomic layers thick and cannot shrink much further. In an April 2005 interview with Techworld, Dr. Moore stated, "We have another 10 to 20 years before we reach a fundamental limit" (Dubash, 2005, 1).

Semiconductor manufacturers face a variety of technical challenges at the nanoscale. Electrons tunnel through flimsy walls several atoms thick causing unwanted electric current leakage out of the circuit. The electricity routing through the IC also generates searing heat which is more and more difficult and expensive to control (Baker and Aston, 2005, 71). Circuit designers must continue to dissipate the heat buildup generated by transistors within a tiny, confined space more effectively. Another serious problem is the growing power consumption for high-performance logic chips. If increasing clock frequency and IC density trends continue, the power consumption of a high-performance microprocessor (MPU) will reach 10 kilowatts within several years and the power density at the surface of this silicon chip could be as large as 1,000 watts per square centimeter which is equivalent to the surface of a rocket nozzle (Iwai et al, 2005, 12). Additionally, power leakage becomes more problematic with shrinking feature sizes, wasting a higher portion of the total MPU power (Intel, 2006, 5). One panelist wrote, "We are far away from the fundamental size limits. . . . The real issue is power dissipation, due to subthreshold slope, which IS a fundamental limit of charge-based devices. Unless we come up with another switch . . . scaling WILL end."

The IC industry has a tradition of blowing past technical barriers with continued ingenuity. Additional IC miniaturization may in fact be more limited by the laws of economics than the laws of physics. Dr. Morris Chang, founder and CEO of Taiwan

Semiconductor Manufacturing Company, said, “Moore’s Law is technologically, but not economically, sustainable . . . because it’s getting too expensive to build new chip fabrication facilities” (Shankland, 2003, 1). These mounting capital burdens threaten to deter or suppress the necessary industry investment to advance device scaling. When Moore’s Law was developed, the costs of building and financing semiconductor manufacturing facilities were assumed to be fixed and negligible (Tuomi, 2002, 6). It is now recognized that complexity comes with a price.

Rock’s Law, named after venture capitalist Mr. Arthur Rock, is the empirical observation that the cost of building fabrication facilities to manufacture chips doubles every four years (Kanellos, 2003, 2). Although chip designers frequently receive most of the attention and credit, the semiconductor industry succeeds or fails based on manufacturing. In 1985, the investment required to build a semiconductor fabricating plant was $100 million (Kanellos, 2003, 2). A new chip-making plant cost four billion dollars in 2006 (Sargent, 2006, 147). This price is projected to reach $10 billion by the end of the decade (Baker and Aston, 2005, 71). Manufacturing infrastructure will soon become prohibitively expensive at this rate of cost growth. By the year 2035, a semiconductor fabrication plant will cost more than the gross domestic product of the entire planet (Wilson et al, 2002, 189)! Historically, companies spend 20 to 30 percent of their profits on capital expenditures; meaning, a fabrication facility can only be justified if it costs about one-third or less of annual revenue (Kanellos, 2003, 2).

Rock’s Law is sometimes labeled Moore’s Second Law. In the future, it may prove to be even more important than the original. In a 2005 interview with Techworld, Dr. Moore acknowledged, “I'm not close enough now to make new predictions - several

things have been called Moore's Second Law but I can't take credit for any of them" (Dubash, 2005, 2). Regardless of what it's called, nanotechnology offers a promising solution to overcome this trend of fabrication plant cost growth.

2.2. Current and Future Feature Sizes

The field-effect transistor (FET) device and the complementary metal-oxide-semiconductor (CMOS) circuit topology have been the standard configuration used to enable IC scaling. Current silicon chips are produced using a 65 nm manufacturing process technology generation. The 65 nm measurement refers to the smallest half-pitch size of the metal interconnect line width connecting transistors, formally known as the technology node (Borsuk and Coffey, 2003, 12). The "technology node" term was developed to provide a single, simple indicator of overall industry progress in IC feature scaling (IRC, 2005, 5). The 2005 ITRS has removed the concept of technology node as the main pace setter for the IC industry (IRC, 2005, i). However, metal pitch remains one of several historical indicators of IC scaling. Figure 2.2 provides a pictorial definition of metal pitch. The physical gate length of the transistor is the computational speed performance driver for processor chips. For the 65 nm technology generation, it is 32 nm. Intel's new 45 nm processor design, called Penryn, is due by the end of this year. Rival Advanced Micro Devices, partnering with IBM, is expected to release its own 45 nm chips by 2008 (Ferguson, 2007, 20).

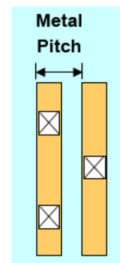
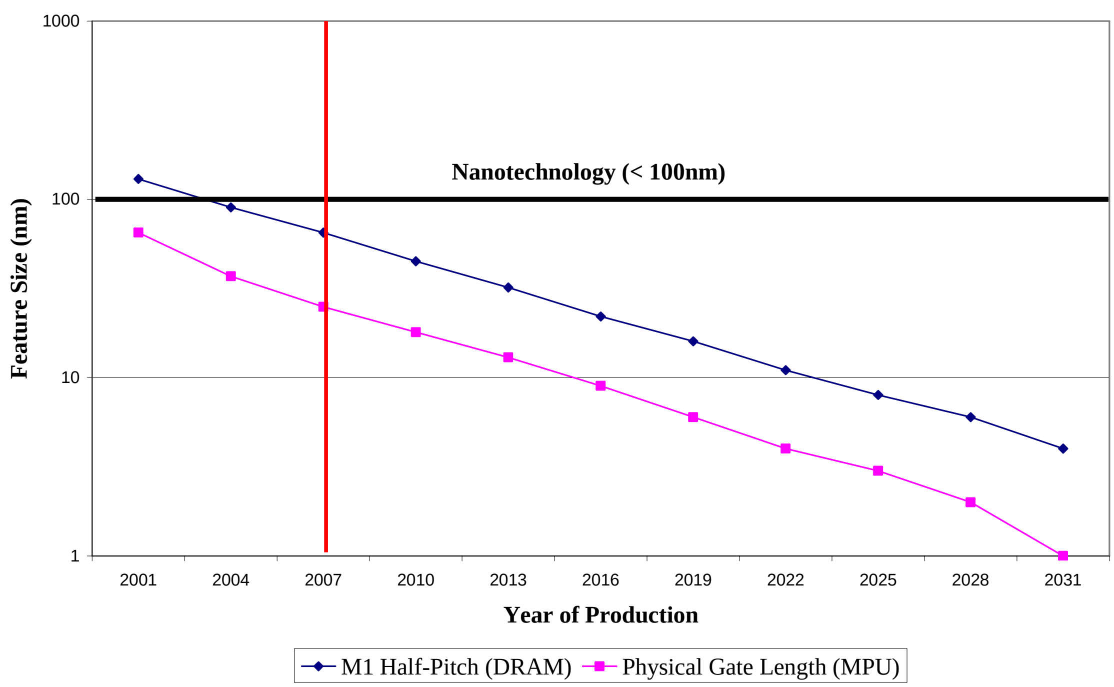


Figure 2.2 2005 ITRS Definition of Metal Pitch

The feasibility of much smaller feature sizes on ICs has been demonstrated by both academia and industry. As an example, Princeton professor Stephen Chou, founder

of Nanonex, successfully created features measuring 6 nm in a lab environment in 2005 (Kanellos, 2005, 1). In its 2006 review of the NNI, the NRC wrote, “Several classes of commercially available lithographic systems—electron beam writers, various contact printing systems, and scanning probe systems—can define structures as small as 5 to 10 nanometers” (NRC, 2006, 103). However, these system capabilitiess currently cannot meet the high-volume demands of IC manufacturing.

Figure 2.3 Product Technology Trends (Logarithmic)



The basic assumption of the ITRS is that Moore's Law, although perhaps slowing down, still provides a good basis for predicting future developments in the semiconductor industry. The ITRS is known to be conservative in its projections. The 2005 ITRS projects a three-year technology cycle meaning the slowing of Moore’s Law’s rate of on-chip transistors (functionality) to doubling every three years rather than the historical two-year pace of change (IRC, 2005, 74). Figure 2.3 uses the 2005 ITRS to present the

dynamic random access memory (DRAM) metal 1 (M1) half-pitch and MPU physical gate length The same market forces will drive the commercial sector to advance non-volatile RAM (NVRAM) and other high-density memory technology closer to fundamental limits. projections out to 2031 on a logarithmic feature size scale. Experts such as Dr. Gerald Borsuk, the Superintendent of the Electronics, S&T Division, at the US Naval Research Laboratory, believe the introduction of a new device and a new circuit topology paradigm will be required to continue Moore's Law beyond 6 to 11 years (Borsuk and Coffey, 2003, 13). He writes, “It is generally accepted that the current device physics paradigm will not permit CMOS switching transistors with well-behaved characteristics with feature sizes on the order of several atoms” (Borsuk and Coffey, 2003, 4).

The semiconductor industry is currently pursuing alternatives to CMOS FET. One such effort is being led by a university-research consortium, the Semiconductor Research Corp (SRC) National Research Initiative (NRI). The NRI is conducting aggressive research in nanoelectronics to develop an information element that can replace the CMOS FET in the year 2020 or beyond and integrate it with CMOS technology (Electronic News, 2006, 60). NRI Director, Dr. Jeffery Welser, believes, “The concept of nanotechnology holds much promise for the continued advancement of the chip industry” (Electronic News, 2006, 60). The 2005 ITRS reflects this growing interest in new nanoscale devices as alternatives to CMOS technology. The ITRS states, “Even though CMOS is (and will remain) the industry workhorse up to and beyond the year 2020, it is anticipated that new devices will be introduced in the latter half of the next decade utilizing different and new ways of processing and storing information” (IRC, 2005, i).

Dr. Richard Silberglitt, Senior Physical Scientist at RAND Corporation, anticipates nanotechnology will play a key role in attaining semiconductor industry goals. Dr. Silberglitt writes, "Nanotechnology will be required to extend Moore's Law to 2015 (using nanoscale silicon technology) and beyond 2020 (using unconventional nanotechnology concepts)" (Silberglitt et al, 2006, 11). Introduction of new materials and modified, CMOS-based device structures will allow some further progress. But, as one panelist wrote, "Scaling below 11 nm will require truly exotic nano-devices that depart radically from the CMOS transistor paradigm." Linear extrapolation of historical trends is not likely to yield accurate predictions in that case.

IC electronics is a mature industry with technologies developed from a cumulative investment of over $100 billion (Dubash, 2005, 1). Therefore, a novel nanotechnology-based concept is unlikely to replace the established electronics paradigm in the near-term future. When interviewed by BBC News in April 2005, Dr. Moore expressed doubt regarding research efforts to replace silicon-based components with technologies and materials developed at the nano-scale. He stated, "Nanotechnology is a very broad field with a lot of applications but I am skeptical that it will replace the more standard silicon technology in the mainstream" (BBC News, 2005, 2).

2.3. Important Advancements and Trends

The panelists were first consulted for their thoughts on the most important advancements and trends that have shaped the nanotechnology in IT development roadmap up to the present. This initial topic serves to identify and baseline current technology drivers as well as establish the vital ingredients of present-day, IT-focused

nanotechnology. Table 2.1, located in Appendix 7, is a prioritized list of the answers given on the subject of important advancements shaping today's nanotechnology in IT development during the two rounds of questioning.

The advancement that the panel reached the highest level of consensus on was the discovery and exploitation of new materials and their associated novel, macroscopic properties. Material science and chemistry at the nanoscale were acknowledged to have led to important breakthroughs in the structures, properties, functions and performance of matter. As an example, one panelist highlighted a recent advancement announced by Hewlett Packard on 17 January 2007. The panelist wrote, "They have combined conventional CMOS technology with nanoscale switching devices, using nanowires, in a hybrid circuit to increase effective transistor density, reduce power dissipation, and dramatically improve tolerance to defective devices." Such performance improvements from nanomaterials are viewed as the fundamental nanotechnology enabler for IT.

Advancements in microelectronics were another area of consensus among the panel. Microelectronics has now breached the nanoscale, critical feature sizes of a transistor have been less than 100 nm for years, making the new label of nanoelectronics appear well-justified. The continued reduction in transistor dimensions is expected to be driven by the aforementioned greater material capabilities as well as new circuit architectures accentuating their nanoscale properties. Two other generally agreed upon responses do not fall within the definition of nanotechnology—plastic electronics and new algorithms for data analysis. The panel recognized these two advancements as prime facilitators of IT-focused nanotechnology. Advancements in plastic electronics are important because they allow conformable, ultra-cheap electronics to be integrated into

systems never before possible, such as on the surface of air platforms. Plastic electronics is recognized as "an important infrastructure for implementing many of the IT-nano capabilities" specifically substrates, packaging and interconnections/communications.

Table 2.1, along with the other data tables in Appendix 7, highlights those responses first given during the second round of questioning. These new responses did not have the benefit of a complete review by all panel members via the Delphi feedback process. It is safe to assume some of these additional inputs would have earned higher scores if a third round of questioning were conducted. It is relevant to note that these second-round responses required a deeper level of reflection on the topic by the panel in order to be raised. This type of stimulation of additional ideas and opinions is expected in the Delphi method and is one benefit of added rounds of questioning.

Table 2.2 lists the panel's views on important trends shaping today's nanotechnology in IT development. The drive toward ever-greater miniaturization of devices, the essence of Moore's Law, was by far the leading response. This scaling of components results in faster and cheaper computing capabilities. The majority of panelists agreed that conventional CMOS scaling will end around the 22 to 32 nm technology generation in 5 - 7 years. The panel felt scaling of components to below 11 nm will require new and innovative nano-devices that depart from the CMOS model.

Two other answers achieved a high-level of accord—modular information-gathering platforms along with increased information access and precision response speeds. The panel inputs on these items were presented in context with the USAF mission. To respond to contemporary enemy threats to US interests, panel members believe the USAF needs IT that will make the force more mobile and agile. The

continued push toward more modular, information-gathering platforms that contain power, sensors, decision making and communications will better enable airmen and their commanders so that the Air Force can be more responsive. Many panelists believe reaction times will need to decrease while accuracy of decisions and precision of response will need to increase. Increased information access speeds are needed to allow US combatants to quickly and correctly assess situations and precisely respond in accordance with policies distributed from higher command.

2.4. Emerging Trends and Limiting Factors

By far the top emerging trend cited by the panel for IT-focused nanotechnology development was post/beyond CMOS technologies. The consensus is the fundamental road blocks for continued enhancement of traditional approaches to transistor scaling and IC manufacturing are very close. Finding a new design/architecture construct—inventing and developing a novel digital switching device for processing information—is the key emerging trend facing the IC industry. The major US semiconductor manufacturers are already funding university research aimed at that objective under the NRI. This eminent shift of IC technology will rebaseline continuous improvement in commercial and military systems. New materials and device structures resulting from nanotechnology may hold the solution to the way forward. Any new nanotechnology-based approach will likely work in conjunction with CMOS computers initially.

Another emerging trend with a high degree of panel consensus is heterogeneous IT integration. As progress slows in device miniaturization, resources are anticipated to shift toward integration of diverse functions. Combining various device technologies

with a nanoscale interconnect is expected to push the physics of how things may be driven and controlled. The heterogeneous integration of non-computational functions, particularly sensing, with electronic and photonic devices may lead to a genuine, global revolution. Other items likely to be integrated with IT capabilities include clothing, the body and other non-traditional places.

The shift from top-down fabrication to bottom-up assembly to make smaller integrated systems also received significant support among panel members as an emerging trend. Appendix 8 provides an overview of the top-down and bottom-up approaches. This anticipated shift is not seen as a replacement of top-down assembly but rather that bottom-up fabrication will play an increasing role in manufacturing processes as devices approach the molecular size scale. One panelist wrote, "I think many applications methodologies will likely evolve to use both approaches synergistically to simultaneously achieve precision, resolution and deterministic placement." A complete list of the panel's responses on emerging trends for IT-focused nanotechnology development is found in Table 2.3.

Table 2.4 contains the prioritized list of emerging limiting factors for IT-focused nanotechnology development. By a considerable margin, power dissipation was agreed to be the ultimate limit to miniaturizing high performance systems. A panelist wrote, "Power dissipation (or more precisely, economic limits to the amount of power that can be dissipated in a particular application) . . . is already limiting the further miniaturization of the silicon transistor. [It] is the main reason that microprocessor clock speeds are no longer rapidly increasing, and growing problems with power dissipation are the main reason that respondents put the end of transistor miniaturization at something like the 22

nm technology node." The various workaround options and recommendations for power dissipation proposed by the panel are preserved within the summary data in Appendix 3.

2.5. Biggest Development Challenges

According to the panel, manufacturing and technology transfer are the principal challenges to developing IT-focused nanotechnology capabilities. Continuing increases in IT capabilities are dependent on ongoing advances in the manufacturing of increasingly powerful computational hardware. The US IT industry's ability to fabricate materials and devices in the lab is relatively easy compared to its feasibility to manufacture complex, heterogeneous, three-dimensional devices with the precision, reproducibility and low-cost needed for a viable technology. The panelists established, "Today, the necessary standards and reference materials needed to develop these manufacturing principles do not exist."

Grace Jean, Senior Editor *National Defense* magazine, wrote, "U.S. investments in nanotechnology have escalated into the billions of dollars in recent years. While scientists and analysts agree such funding is advancing nanoscience research, they explained that moving the resulting discoveries and materials into the market remains one of the industry's toughest challenges" (Jean, 2005, 20). The panel's proposed solutions to the challenge of technology transfer, from lab bench to field (also known as, the "Valley of Death"), focused on the requirement for a better process. The process should identify ideas with the best chance of being fielded then apply adequate resources to bring the technology to a level of maturity necessary to make it usable.

The panel stressed the need to target funding toward bridging the Valley of Death. Even with budget constraints, a more efficient cycle of technology development should be pursued to bring scientists, engineers and customers together at earlier stages in the technology realization process. Panel members agreed, “Right now, scientists don’t really understand how they can have an impact that could be fieldable and engineers don’t always understand what clever design could be manufacturable. Bringing these groups together to value their respective strengths . . . would create a new paradigm in nanotechnology and engineering.” Other panelist answers to the key developmental challenges are reflected in Table 2.5 with associated views in Appendix 3.

SECTION 3: NANOTECHOLOGY’S CONTRIBUTION TO IT IN 2030—“THE ART OF THE POSSIBLE”

3.1. Nanotechnology-Enabled, IT Capabilities

To design and evolve insightful long-term, strategic plans, the USAF must gain a deeper understanding of IT-focused nanotechnology capabilities and developments that have matured to an appropriate level to benefit operations in the year 2030. The classification of Technology Readiness Level 6 (TRL-6) is traditionally the technology measurement used within the US Department of Defense (DoD) to designate this point of development. TRL-6 is defined as the level of technology maturity where a system/subsystem model or prototype demonstration has successfully occurred in a relevant environment, such as a high-fidelity laboratory or simulated operations (Defense Acquisition University, 2006, np). Table 3.1 contains the panel’s views on the most likely nanotechnology-enabled TRL-6 or greater IT capabilities by 2030.

Orders-of-magnitude better computing capabilities nearly attained unanimous approval. However, opinions varied on the state of computer performance in 2030. IT systems are expected to either exploit performance accelerations from re-engineering software layers, massive parallelism and extensive use of special-purpose hardware; and/or, benefit from the development of one or more successors to the silicon transistor. Most panelists thought a successor to the transistor would be found by the commercial sector. It is anticipated that nanotechnology will play an increasing role, not only for the electronics computation engine, but also for interconnects, cooling and packaging.

The various panelist performance estimates are primarily extrapolations of ITRS trend information which is a conservative, linear estimate. A 100,000X increase in performance/cost over the next 25 years was the most common figure quoted. Such increased computation power "will be able to create simulation environments for designing and optimizing advanced aircraft with a fidelity rivaled only by actually building the system but with a turn around of hours rather than years." These smaller and faster computers have the potential to enable totally autonomous fighter aircraft "so fast that no human could fly them remotely—instead they will keep up a running dialog with a human operator, receiving instructions and sending information, but making all tactical 'decisions' on board in real time."

In addition to smaller and faster computers, the panel expects nanotechnology to enable low power, high density storage. At traditional Moore's Law rates, storage would be in the range of one to 10 petabits, or one quadrillion (10^{15}) binary digits, with a cost of about $100. Persistent surveillance capabilities to find, observe and precisely target enemy threats were also assessed to be TRL 6 or greater by 2030. The USAF will need

these capabilities to gather needed intelligence outside of cities and other locations where access to commercial surveillance systems is not possible.

3.2. Global Impacts of Nanotechnology in IT

The panel coalesced on improved connectedness through better and faster communications as the most likely impact of nanotechnology in IT on the world in 2030. In general, respondents discussed the impact of IT but failed to clearly highlight nanotechnology's effect on IT. However, the consensus is that future communications and data processing will further revolutionize how we interact with each other and our environment. "This will change how confrontations occur (e.g. in cyber space, on the network, etc) and introduce new vulnerabilities as well as new capabilities."

A parallel development, also enabled by nanotechnology, is the creation of small, cheap sensors. This is the second-leading panel response. Panelists echoed the belief that IT-focused nanotechnology development and integration of sensor and communication technologies will lead to smart networks, instantaneous information access and significantly better persistent surveillance and situation awareness. These small sensors can be widely distributed in the environment to gather, analysis and distribution information. One innovative scenario proposed the idea of "an artificial fly that can record audio and video and then transmit that information in a secure manner to a host." The USAF could use such stealthy capabilities to monitor even the most hidden of opponents and better target weapons to achieve desired effects. Table 3.2 prioritizes all panel responses to the most likely impacts of nanotechnology on IT in 2030.

3.3. Relevant Nano-IT R&D Driven by Commercial Marketplace

The commercial marketplace will drive nanotechnology R&D in areas which can be leveraged by the USAF. The extensive application of IT devices along with the competitive advantage that comes from making them "smaller, faster, cheaper" will drive economic investment for continued industry improvements in nanofabrication technology. However, a different set of requirements and specifications exist in the commercial sector. More specialized DoD applications derived from commercial products will still require a separate, development infrastructure. Table 3.3 lists the prioritized, panel responses to the question of nanotechnology R&D relevant to future IT driven by the commercial market. Two answers achieved the highest level of agreement—solution to the scaling bottleneck and high-density memory.

The commercial sector will strive to maintain the pace of Moore's Law by developing devices and tools to solve current barriers to further miniaturization. It would be fruitless for the DoD to invest its precious resources to help squeeze the most out of CMOS FET technology scaling. The commercial industry has mastered this area and has the ability and motivation to apply large amounts of resources toward the problem (Borsuk and Coffey, 2003, 17). The same market forces will drive the commercial sector to advance non-volatile RAM (NVRAM) and other high-density memory technology closer to fundamental limits. As industry reaches traditional silicon manufacturing process limits, it will turn to nanotechnology to solve the difficult problems associated with scaling logic and memory devices under 25 nm. However, as one panelist cautioned, "This industry investment in new devices and materials for scaled logic may

slow down and be diverted if translation of the many nanotechnology ideas into product does not happen within the expected Moore's Law predicted timeframe."

3.4. USAF Mission Elements Most Impacted

The panel anticipates IT advances of the next 23 years will allow a revolution in aircraft as well as their associated systems. The top two, panel responses on the topic of USAF elements most impacted by IT-focused nanotechnology reflect slight variants of this theme—specifically smaller, autonomous vehicles and improved, remotely piloted vehicles. Smaller, autonomous vehicles with increased sensor integration, computing and communications capabilities due to embedded nanotechnologies will reduce the need for manned aircraft and transform the way the USAF fights. These autonomous systems will greatly enhance the ability to gather more information and pinpoint threats from the air. Technology will remove the pilot from many current missions; however, the panel warns that USAF must be sensitive to the harmful consequences of becoming over-dependent on such systems, such as detachment from or indifference toward the operation.

Progress in nanotechnology will greatly enhance the capacity of future IT capabilities allowing remote-pilot-assist systems to further replace traditional pilots. A rational extrapolation of trends in performance, power requirements and compactness of IT systems supports a scenario where airplanes fly themselves with human operators providing general directions and receiving confirmations of mission orders and results. "By taking the pilot out of the airplane, the power to mass ratio will be much larger, the volume of the aircraft will be much smaller, the speeds and accelerations will be much larger, and the radar cross section will be much smaller."

Remote sensing enabled by low-cost massively distributed nano-sensors will allow the USAF to monitor nearly the whole world in real time. However, adversaries will also have the ability to better monitor us. Swarms of redundant, networked sensors on small satellites, radar systems or other reconfigurable platforms with improved on-board computing are made possible by nanotechnology. One panelist noted, "A blue-sky idea is animal (or insect)/electronic hybrids, utilizing biopower for mobility, system power, and communication)." Such sensor meshes will impact personnel and physical security and surveillance and be a lot harder to destroy than their current counterparts. Table 3.4 contains the complete list of panel responses concerning USAF mission elements most impacted by IT-focused nanotechnology.

SECTION 4: CONCLUSION AND RECOMMENDATIONS

4.1. Best USAF Investments in Nanoscience and Nanotechnology

The US DoD had tremendous influence on computing R&D through the 1960s when costs were extremely high as the technology gave them capabilities they couldn't get any other way (Dubash, 2005, 2). Since then, commercial industry surpassed the DoD in aggregate, R&D spending. The disparity between defense and commercial investment in R&D means that the technology development in the US is being driven to a greater extent by commercial market forces rather than the defense market. Given shrinking defense budgets and the amount of research conducted by the private-sector, the USAF must be selective on where it spends its investment dollars to achieve the greatest impact and leverage commercial-of-the-shelf technology, where possible, to meet its performance requirements.

Nanotechnology is equipped to meet unique, USAF IT demands unsatisfied by the commercial marketplace. Table 4.1 contains the panel's recommendations on astute USAF fiscal spending in nanotechnology to best enable IT capabilities to support its mission. The proposed investments factor in the R&D capital expenditures of the commercial sector covered in Subsection 2.1 and the nanotechnology in IT threats discussed in Appendix 12. These investments are intended to stimulate innovation and bridge the "Valley of Death" on nanotechnology important to the USAF.

While the military will benefit from commercial, advanced sensor development efforts, the USAF will need to invest in advanced, autonomous sensor systems. This position achieved the highest level of agreement among the panel. The national defense requirements tend to be far more stringent than those found in the commercial sector. The USAF, and the other military services, will likely want better sensitivity per detector and more redundancy in the sensor system to identify false positives. One panelist noted, "Specialized components such as sensors will not necessarily be subject to the same global economics, and USAF funding of research directed towards development of such specialized components should provide value."

The emergence of nanotechnology over the coming decades will have implications to national defense and the conduct of war. IT-focused nanotechnology has an enormous potential to combat terrorism and other US threats when applied to security capabilities such as "hardware (e.g., the encoding of hard-wires security codes in electronics), goods (e.g., sensors to detect contamination), and personnel (e.g., DNA and biochemical tags for friend/foe, at a distance; and low-cost, distributable explosive sniffers)." One panelist wrote, "The commercial sector is not concerned about malicious

intrusions into their hardware and software to the same extend that the DoD should be." The DoD should target and cultivate security capabilities, to include anti-tamper technologies, that guarantee trusted IT systems as well as undermine malicious, adversary abilities.

4.2. Policy Issues Senior USAF Leaders Should Tackle

In addition to its funding, the USAF must understand where to best spend its time to enable nanotechnology in IT success. This area of interest is the focus of the question on policy issues that USAF senior leadership should tackle to enable IT-focused nanotechnology. The collected responses to this topic are contained in Table 4.2. Overwhelmingly, the policy issue the panel settled on is expanding USAF commitment to long-term, fundamental research, also known as the 6.1 budget. The USAF and other national defense agencies need to continue to invest in leading-edge research to maintain a performance advantage.

The USAF has benefited immeasurably from past investments in high-risk, high-payoff technology research in materials, IT and other areas. The DoD has been a leading advocate for this type of research in the past, but has not maintained its commitment under growing pressure to address near-term requirements such as detecting and destroying improvised explosive devices. One panelist wrote, "<u>The funding system for risky, blue-sky research in the US is broken</u>. . . . Industrial research labs essentially no longer exist, and it is doubtful they will ever come back due to the present economic models. DARPA used to be the last bastion – but no more, with very targeted projects, and no sustainability."

Greater advanced technology advocacy and sponsorship, not only within the USAF but across the US, is critical to realize the knowledge discovery payoffs from long-term research. The panel stressed the need to push the US government to rebuild the basic research budgets and the associated infrastructure of the services. One panelist put forward that this means quadrupling the budget numbers over the next decade. This panel member went on to write, “The cuts in 6.1 funding for universities is devastating our engineering schools—this is really the most important investment our military can make in our future.” The USAF should also strongly support National Science Foundation and Department of Energy basic S&T research efforts. Panelists identified the need to invest time to encourage continuous improvement of the research process itself. The USAF should deliberately target its research process and make it a major multiplier to the research agenda.

The second-leading response expresses the related need for the USAF to help promote positive environmental conditions to grow a technology workforce of educated airmen and US contractors with the scientific knowledge to develop and use nanotechnology. One panelist cautioned if organizations such as the USAF do not create the conditions necessary for people to thrive in IT careers, American citizens will be unable to perform the required technical jobs. This panelist petitioned, “What do we do then—contract the work out to China?” An additional area of panel concern is the fact multinational companies are increasingly moving to foreign countries, as one panelist put it, “not because things are cheaper there, . . . [but] because that is increasingly where the infrastructure and the talented people are.” The US must confront the fact that many,

large multinationals could become effectively Chinese or Indian-based companies if current economic trends continue.

4.3. USAF Technology Investment Strategy

The 21st Century Nanotechnology R&D Act of 2004 funnels approximately a billion dollars per year into US government nanoscience R&D through 2008. Table A10.1 and Figure A10.1 located in Appendix 10 provide a year-by-year perspective on the NNI R&D budget. The DoD budget figures are a percentage of the overall federal government investment in nanotechnology; and, the USAF is a percentage of that percentage. The international budget for nanotechnology R&D is several times larger, with every major economic power and many developing economies investing considerable resources (Silberglitt, 2006, 10).

The next 23 years promise radical developments in nanotechnology pushing the limits of physics. The USAF must secure sufficient, steady funding for IT-focused nanotechnology and collaborate with industry to maintain its technological superiority. The USAF must invest in the early stages of R&D where the maximum leverage in development programs occurs and investment costs are low to nurture long-term, IT-focused nanotechnology research within the US government, industry and university laboratories (Borsuk and Coffey, 2003, 16-17). The commercial sector, which has more pressing near-term needs, is not likely to invest in long-term, basic research—by its nature nonproprietary—without governmental encouragement (Borsuk and Coffey, 2003, 16). The key to successful collaboration is positioning the USAF so it can maintain the needed wide visibility in the technical community and recognize important IT-focused

nanotechnology breakthroughs (Borsuk and Coffey, 2003, 17). By targeting its precious time and money investments on high-value, mission-oriented capabilities not driven by commercial needs or interests, the USAF can achieve the greatest benefit from nanotechnology in the realm of IT.

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APPENDIX 1: DELPHI QUESTIONNAIRE #1

USAF "Blue Horizons" Research Program—Data Collection Questionnaire #1

Section A. Introduction

The mission of the US Air Force (USAF) is *"to deliver sovereign options for the defense of the United States of America and its global interests—to fly and fight in Air, Space, and Cyberspace."* The notion of "sovereign options" is explained as "an array of options . . . options that are not limited by the tyranny of distance, the urgency of time, or the strength of our enemy's defenses. With one hand the Air Force can deliver humanitarian assistance to the farthest reaches of the globe, while with the other hand we can destroy a target anywhere in the world." An increased awareness of the promise of, and symbiotic interactions among, emerging technologies is a prerequisite for the USAF to succeed in this mission statement within the context of the transforming world environment.

The USAF has selected you to participate in this Delphi study based on your subject-matter knowledge and experience. ***The objective is to forecast the most probable future state of nanotechnology in the realm of information technology (IT) in the year 2030.*** This is the first of two rounds of questions. This initial questionnaire is designed to elicit your informed judgments and insights on the topic of nanotechnology as applied to IT. Please compose narrative responses to include your argument(s) and relevant evidence for each question in Sections B and C. The primary audience for this data is the Chief of Staff of the Air Force and his senior leadership. While highly intelligent, these military professionals are not technical experts in nano- and/or computer science. Therefore, be sure to describe complex or technical issues using terms someone without professional training in those subject areas can understand.

The responses from all the panel members to these questions will be synthesized to help formulate the second-round questionnaire. As an underlying tenet of the Delphi method, all panelist responses will be non-attribution in the sense that none of the panel members' statements will be credited to them by name in this process.

The following two key terms are defined up-front to insure a common perspective:

- Per the National Nanotechnology Initiative, ***nanotechnology*** is *"the understanding and control of matter at dimensions of roughly 1 to 100 nanometers, where unique phenomena enable novel applications."*
- Per the Clinger-Cohen Act of 1996, ***information technology (IT)*** is *"any equipment or interconnected system or subsystem of equipment, that is used in the automatic acquisition, storage, manipulation, management, movement, control, display, switching, interchange, transmission, or reception of data or information . . . includes computers, ancillary equipment, software, firmware and similar procedures, services (including support services), and related resources."*

Paradigm shifts alter the rules and regulations that set limits or establish boundaries and offer applicable problem-solving guidance. Such revolutionary changes often occur when two or more technology areas converge. For example, the merging of information technology and biotechnology has spawned “bioinformatics” and a genomics revolution. This questionnaire explores the revolutionary change anticipated with the convergence of nanotechnology and information technology.

Section B. “The Art of the Possible” – Nanotechnology’s Contribution to IT in 2030

1.) What advancements and trends have been important in shaping today’s nanotechnology in IT development roadmap?

2.) Do you think these trends will continue? Why?

3.) *[Technology Readiness Level 6 (TRL-6) is defined as the level of technology maturity where a system/subsystem model or prototype demonstration has successfully occurred in a relevant (e.g. high-fidelity laboratory or simulated operational) environment.]* What nanotechnology-enabled IT capabilities do you anticipate will be at or above TRL-6 by the year 2030?

4.) What is the biggest challenge(s) to overcome, obstacle(s) to progress, in developing these nanotechnology capabilities for use in IT systems in the year 2030? Why?

5.) What impact will nanotechnology in the realm of IT have on the world in 2030?

6.) What potential “technology surprises,” i.e. technological developments that could undermine US military preeminence, do you anticipate with IT-based nanotechnology in 2030 resulting from the forces of globalization and commercialization?

7.) Two facts have emerged from the current Global War on Terror—this is going to be a long, "Cold War-like" conflict and our adversaries are very technologically savvy. With that in mind, what threats do you envision coming from terrorists combining nano- and information technologies in new and dangerous ways that will impact the USAF mission in 2030 and beyond?

Section C. Proper Sector Roles and Responsibilities – Defense versus Commercial

Context: The US Defense Department (DoD) wielded enormous influence over leading-edge technology development efforts in the past. In 1965, commercial industry surpassed the DoD in aggregate, research and development (R&D) spending. The disparity between defense and commercial investment in R&D has been growing wider ever since. This difference means that the technology development in the US is being driven to a greater extent by commercial market forces rather than the defense market. Given shrinking defense budgets and the amount of research conducted by the private-sector, the USAF must be selective on where it spends its investment dollars to achieve the greatest impact.

1.) What area(s) of nanotechnology R&D relevant to future IT capabilities do you envision the commercial sector and global marketplace driving? Explain.

2.) What USAF mission element(s) could be most impacted in 2030 by advances in nanotechnology in IT? How?

3.) What policy issues should senior USAF leaders tackle to enable the full potential of nanotechnology-enabled IT capabilities in 2030? How?

4.) What about the global market versus USAF market's needs in 2030 have I not asked that you feel is pertinent?

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APPENDIX 2: DELPHI QUESTIONNAIRE #2

<u>USAF "Blue Horizons" Research Program—Data Collection Questionnaire #2</u>

<u>Section A. Introduction</u>

This second, and final, round of questions is intended to advance the US Air Force's (USAF) analysis of nanotechnology as applied to information technology (IT). The value of the Delphi method rests with the ideas it generates, both those that evoke consensus and those that do not. This questionnaire is designed to allow further exploration and deliberation on various complex topics collectively in order to crystallize areas of consensus as well as explore reasons for disagreement. The USAF greatly appreciates all your efforts to date in examining the promise of, and symbiotic interactions between, nanotechnology/nanoscience and IT in support of the service's mission within the context of the transforming world environment.

For this second-round questionnaire, **each panel member is requested to reassess his/her original inputs based upon examination of the group's range of responses to determine the most probable scenario(s).** The open exchange of ideas is encouraged in this process. Panel members are asked to endorse and/or refute other submitted responses with any facts at their disposal. The essence of this structured communication is the process of reaching an understanding of how the group views each issue. This reflective process relies heavily on the level of detail in the responses the panel members provide. As an underlying tenet of the Delphi method, all panel members' answers will not be attributed to them by name in order to encourage free and open debate.

The structure of this second questionnaire remains relatively consistent with the first. However, the format has changed. Following the Delphi style, the narrative responses received on the first questionnaire have been consolidated and fed back in the form of organized listings for the group's consideration. These responses are presented in blue font after the derived answer statement. Section D has been added to pose some additional questions back to the group on a few germane topics brought up by panel members during round one. Narrative responses to include your argument(s) and relevant evidence are again requested for each question in Sections B, C, and D. **Please place additional emphasis on your response(s) to <u>Topic #11</u> as it is the crux of this study.**

The Delphi method offers a systematic means to perform technology forecasting by synthesizing your informed opinions with those of other subject-matter experts. The inputs you are providing via these Delphi questionnaires will play a key role in helping shape USAF strategic planning. The final report for this study will be presented to the Chief of Staff of the Air Force (CSAF) and his staff in June of 2007, and will serve as an input for the development of service budgets, war games, the Strategic Planning Guidance, and the Quadrennial Defense Review. While highly intelligent, these military professionals are not technical experts in nano- and/or computer science. Therefore, be

sure to describe complex or technical issues using terms someone without professional training in those subject areas can understand. Also, continue to orient your answers toward better illuminating the research objective: **the most probable future state of nanotechnology in the realm of IT in the year 2030.**

Section B. "The Art of the Possible" – Nanotechnology's Contribution to IT in 2030

Topic #1: The important advancements and trends shaping today's nanotechnology in IT development roadmap. *(Please read through the various, panelist responses synthesized below in blue font then answer the associated question at the bottom.)*

(Important Advancements)

(a) Microelectronics

(b) Optoelectronics

(c) Mechanical Microsystems

(d) New Algorithms for Data Analysis

(e) Instrumentation and Tools:

-- Capable of nanoscale imaging, characterization, fabrication, and manipulation.

(f) Lithography:

-- IT systems demand complexity, only possible through the integration enabled by parallel processing.

-- Although next generation lithography systems are tremendously complex and expensive, viable alternatives have not been identified to create useful integrated systems.

(g) Materials:

-- There is a shared vision that nanoscience and nanotechnology will dramatically change the performance and function of materials and devices by capitalizing on changes in the structure-property-function of materials when made at the nanometer length scale.

-- Continued improvements in system performance have been enabled by the underlying materials technology, for example, strained silicon and GaN.

-- New IT capabilities, for example, the use of Carbon NanoTubes (CNT) in memory devices has resulted in larger memory systems that are also potentially radiation hardened.

-- IBM has developed a product they named Millipede which is a chip containing more than 1,000 heated areas that can make, or read, tiny indentations in a polymer film.

-- Currently advancement in nanotechnology is a material science endeavor for both properties and fabrication.

(h) Nonvolatile Memory:

-- Present NVRAM has enabled portable, compact, low power IT systems. Advances in this area may well transform the way IT systems are structured.

(i) Displays:

-- New displays are being developed by Motorola that are based on CNT technology—a breakthrough technique that could create large, flat panel displays with superior quality, longer lifetimes and lower costs than those currently available.

-- The CNT is an electron emitter capable of serving as the backplane of a flat-panel display enabling new televisions with no high-voltage components. . . .The US is out of the business today.

(j) Plastic Electronics:

-- Although not "nano", plastic electronics for conformable and ultra-cheap electronics is alone very important, and is an important infrastructure for implementing many of the IT-nano capabilities (i.e. as substrates, packaging, and interconnections/communications).

(k) The International Technology Roadmap for Semiconductors (ITRS) Planning Process:

-- Has resulted in the fantastic progress in the past decade as everything got more complex.

-- A world-wide collaboration among the suppliers, developers and manufacturers of all types of semiconductor chips and the equipment to build them to plan out the steps that are needed for the entire industry to stay at or above Moore's Law, however you want to understand that. The entire community analyzes the current state of all of the component technologies (there are now at least 100 different issues being tracked), understands which ones require additional attention, and then plans how to achieve the industry goals. The roadmap comes in both 'near term' (0-6 years) and 'long term' (7-12 years) segments – the near term essentially representing what is in today's development environment and the long term is what the industry is planning on.

-- After collaborating and cooperating on understanding what objectives need to be met by every segment of the industry, the individual companies then compete fiercely to be ahead of everyone else in actually delivering.

(Important Trends)

General Comments:

-- Nature has shaped most of the IT development roadmap in terms of trends of development at the beginning, while performance, cost, and scalability are now driving the roadmap.

(a) Modularity:

-- Push toward modular information-gathering platforms containing power, sensors, decision making and communications.

-- The "new" enemy is very mobile and agile, and so the IT that is needed in the hands of the USAF is that which will make the force more mobile and agile. . . . key technologies will enable the people and decision making so that the force can be more responsive.

(b) Increased Information Access Speeds:

-- Need to allow combatants to make timely assessment of situations and act in accordance with policies distributed from command centers.

-- Reaction times will need to decrease, accuracy of decisions will need to increase, and precision of response will need to increase.

(c) Miniaturization of IT Devices (Especially Transistor Dimensions)—Resulting Increased Information Processing and Storage Capabilities:

-- Fundamental limits in precision and size are created by the atomic nature of matter—still a long way away from these limits. If trends continue to this limit we will be able to manufacture complex computational systems in which the fundamental elements are made from some modest number of precisely arranged atoms.

-- IT has been driven by “smaller = faster and cheaper”. Periodically, IT devices have been reinvented – always in a way that has enabled further miniaturization.

-- Scaling leads to more transistors per area leading to less expensive chips for given performance and to faster computational speeds. Uncertainty over technical challenges at the nanoscale increases risk with time in achieving the scaling stated in the ITRS.

-- Consensus is that conventional complementary metal-oxide-semiconductor (CMOS) scaling will end around the 22 to 32 nm node in 5-7 years. Scaling of devices to below 11 nm will require truly exotic nano-devices that depart radically from the CMOS transistor paradigm. However, the accuracy of these technology predictions is suspect due to the departure from conventional scaling.

-- Microelectronics as we know it today is a product of nanotechnology. The critical feature size of transistors has been below 100 nm for several years. The critical layer thickness of a transistor has been less than 100 nm for over 10 years. The continued reduction in transistor dimensions is accentuating their nano-scale properties.

-- Nanotechnology is having a profound impact in shaping the semiconductor industry roadmap and future technologies for memory and information storage. Today’s logic chips and mass storage technologies already incorporate nanotechnology. The logic chips in production have 35 nm gates and giant magnetoresistance wire technology revolutionized the hard drive industry.

-- There is still a need for smaller, faster, cheaper computing capabilities which includes processors, displays, memory devices, etc. And, the commercial sector will continue to drive this development as long as that need exists for large volume systems.

(d) Far from Known Limits of Fundamental Physics:

-- Even though nearly everything about our devices for measurement, computation and communication will change significantly over the next 25 years, the total rate of improvement in the capability of our information systems will continue to increase at historical rates. This can happen because although we are starting to push the limits of particularly materials and technologies, such as silicon and the field effect transistor, we are no where close to the known limits of fundamental physics for our ability to capture, store, process, transmit and display information.

(e) World-Wide Cooperation and Competition:

-- Driver for primary prediction—that at all scales at which we work, our IT devices and systems will have 100,000 times the capability that they have today – e.g. they will keep up with the historical rate of improvement in total capability.

(f) Greater Precision in Manufacturing:

-- Toward greater precision in the manufacturing process, greater flexibility in what is manufactured, and lower manufacturing cost. In the context of computer hardware, these trends are exemplified by Moore’s Law, with exponential increases in memory size, computational power, communications bandwidth and related metrics.

(g) Increasing Amounts of Information to Gather and Analyze:

-- Small, integrated systems enabled by nanotechnologies can help gather information to separate fact from fiction, make accurate decisions, and understand and influence actions and opinions.

(h) Distributed Information Gathering and Decision Making

(i) Desire for More Data Storage

(j) Desire for Faster Data Processing

What is your judgment of the various responses based on your knowledge and the supporting arguments presented? Focus on and discuss in greater detail only those prospects you regard as the most important advancements and trends shaping today's nanotechnology in IT development roadmap.

Topic #2: The emerging trends and limiting factors for nanotechnology in IT development. *(Please read through the various, panelist responses synthesized below in blue font then answer the associated question at the bottom.)*

(Emerging Development Trends)

General Comments:

-- Nanomedicine will push the development roadmap.

(a) Heterogeneous Integration:

-- Combining various device technologies with a nanoscale interconnect—not yet driven by mainstream commercial interests.

-- Will push the understanding of the physics of how "objects" may be driven and controlled at the nanoscale.

(b) Shift from Top-Down Fabrication to Bottom-Up Assembly:

-- Trends to make smaller integrated systems will continue with a shift toward bottom-up assembly of nanotechnologies, distributed communications, and better algorithms for more efficient data analysis and decision making.

(c) New Metrics:

-- By 2030, IT trends will evolve to be very different from what we see now. The pace of improvement will be measured by metrics other than technology node, as 1 nm and below is the scale for a single atom. Raw processor speed may be de-emphasized while overall computational operations per second will continue to be a metric. Integration density per volume may become a metric as 3D integration improves.

(d) New IT System and Logic Devices (Various Alternatives Proposed):

-- Highly integrated IT systems will include RF, MEMS chemical and biological devices.

-- Sophisticated "context-aware" IT systems will be available by 2030 with high levels of sensory perception and internal actuation to physically adapt over time.

-- Very close to the end of the transistor "shrink". Processor clock speeds have already leveled off, although device densities are still increasing. The primary question for leading electronics manufacturers is this: How long can the engineering teams around the world introduce new materials, fabrications processes, and FET device architectures at the furious rate needed to continue the shrink while keeping device performance roughly constant? Once clock speeds start to seriously decline that game will be over. What will be left is the possibility of inventing and developing a new digital switching device for the processing of information. The major US semiconductor manufacturers are already funding university research aimed at that objective under the Nanoelectronics Research Initiative (NRI).

-- Traditional approaches to transistor scaling and integrated circuit manufacturing are rapidly approaching fundamental road blocks to continued improvement. The industry is

projecting that a fundamental change will be needed in integrated circuit manufacturing in the 10 to 20 year timeframe. New materials and devices structures resulting from nanotechnology may hold the solution to the way forward. Alternatively, new circuit architectures that can make more effective use of available hardware may enable the continued increase in computational power without radical changes in the underlying transistor structures. Either way, it is clear that the historical approach can not continue. This eminent shift of integrated circuit technology will change the basis of continuous improvement in commercial and military systems.

-- Silicon Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFET)
-- Ferroelectric Field Effect Transistors
-- Quantum Transport Devices based on Resonant Tunneling
-- Single-Electron Devices for Logic Applications
-- Superconductor Digital Electronics
-- Quantum Computing using Supercomputers
-- CNT for Data Processing
-- Molecular Electronics

(e) Molecular Computing Using Biological System:

-- Will be challenging, but can be achieved in future.

(f) Assembly Technology at the Nanoscale:

-- May move to play a greater role in integration.

(g) Directed Assembly and Self Assembly:

-- Revolutionary advances can be expected in the next 25 years.
-- A merging of integration technologies will blend new batch-fabrication (i.e. fabrication on wafers) with these assembly techniques to create best-of-class IT systems.

(h) Automatic Configurable and Reconfigurable IT Systems:

-- Will become available by 2030.
-- One such vision is to create hardware that can rewire itself on demand at very fine granularity. Such systems may solve relatively near-term technical challenges and, farther in the future, could evolve into computational systems with the ability to learn how to improve their performance with experience and the tools to implement these improvements in situ *(in the original position)* within their hardware.

(i) Random Access Memories (Various Alternatives Proposed):

-- High-Permittivity for DRAMs
-- Ferroelectric Random Access Memories
-- Magnetoresistive RAM

(j) Mass Storage Devices (Various Alternatives Proposed):

-- Magneto Optical Devices
-- Rewritable digital video disks based on Phase Charge Materials (PCM)
-- Holographic Data Storage
-- Analog Front-end Chip for a MEMS (AFM)-based Mass Storage—The Millipede Concept

(k) Data Transmission and Interfaces (Various Alternatives Proposed):

-- Transmission on Chip and Board Level
-- Photonic Networks
-- Microwave Communications System—Novel Approaches for Passive Devices

-- Neuroelectronic Interfacing: Semiconductor Chips with Ion Channels, Nerve Cells, and Brain
(l) Sensor Arrays and Imaging Systems (Various Alternatives Proposed):
-- Optical 3-D Time-of-Flight Imaging System
-- Pyroelectric Detector Arrays for IR Imaging
-- Electronic Noses
-- 2-D Tactile Sensors and Tactile Sensor Arrays
(m) Displays (Various Alternatives Proposed):
-- Electronic Paper
-- Liquid Crystal Displays
-- Organic Light Emitting Devices
-- Field-Emission and Plasma Displays

(Emerging Limiting Factors)
(a) Statistical Uncertainty in the Placement of Individual Dopant Atoms:
-- One limiting factor in the miniaturization of Field Effect Transistors (FET)
-- Precise placement of dopant atoms would likely be necessary to enable the ultimate miniaturization of such devices.
(b) Power Dissipation:
-- Ultimately limit high performance systems (reference the ITRS).
-- There appear to only be three ways around this: i) identify new devices that consume less power (a daunting task, since the physical limits of charged-based devices are fundamental, not technological); ii) identify new architectures; and iii) look for new opportunities for blending electronics with other low power information systems (e.g., biological). The second is the most viable short-term option, while the third is a revolutionary approach for potentially interfacing machines to humans.

What is your judgment of the potential of the various responses based on your knowledge and the supporting arguments presented? Focus on and discuss in greater detail only those prospects you regard as the major emerging trends and limiting factors of nanotechnology in IT development.

Topic #3: The nanotechnology-enabled IT capabilities anticipated to be at or above TRL-6 by the year 2030. *[Technology Readiness Level 6 (TRL-6) is defined as the level of technology maturity where a system/subsystem model or prototype demonstration has successfully occurred in a relevant (e.g. high-fidelity laboratory or simulated operational) environment.] (Please read through the various, panelist responses synthesized below in blue font then answer the associated question at the bottom.)*

General Comments:
-- Depends upon the commitment of sufficient investment and resources to the development of a given technology for a specific application.
-- Various nanoscale devices currently being studied by physicists will have matured by 2030 toward engineering prototypes. 24 years is ample time for progress on integrated

platforms for a subset of the successful devices. (ITRS map has this happening sooner – 15 years.)

(a) Better Computing Power—Smaller, Faster Computers (Various Alternatives Proposed):

-- A single processor equivalent will outperform the largest of today's existing supercomputers on a power budget of a few hundred Watts. In other words, it will have the data handling capacity of 10 human beings. Such systems will make totally autonomous fighter aircraft possible (they will have the equivalent of a crew of 10), but they will be able to maneuver at accelerations that would kill any living thing and make decisions in microseconds. These autonomous systems will be so fast that no human could fly them remotely—instead they will keep up a running dialog with a human operator, receiving instructions and sending information, but making all tactical 'decisions' on board in real time.

-- >1,000X speed increase

-- Systems able to perform a trillion-trillion logic operations per second (10^24) in a computer smaller than today's pocket calculators. Manufacturing costs for these systems will be under a dollar.

-- Nanotechnologies should provide small, fast computers that can be part of multi-functional materials, e.g., they can be embedded in clothing, structures, or other materials thereby reducing size, weight and providing additional capabilities.

-- *(Either)* Silicon transistors will have matured, and no better substitute for information processing will have been found, in which case, technological advances in devices and circuits will occur at the slow rate found in other mature "systems technologies" such as transportation. IT systems will exploit massive parallelism and extensive use of special-purpose hardware to accelerate common tasks. Hardware may be highly reconfigurable, even at a fine-grained level. Optical communications will be standard for all communications over lengths greater than chip scale, and may be used for on-chip buses as well. There will be a great effort underway to wring performance improvements from drastic simplification of todays overly layered and grossly inefficient software stacks. In general, innovation will be focused on areas other than the device.

(Or) One or more "smaller, faster, cheaper" successors to the silicon transistor will have been found and successfully developed for commercial applications, in which case, the cost-performance of IT systems could still be compounding at current exponential rates or higher.

-- Highly likely that computation power that is limited today to supercomputer class machines that are extremely expensive and require large amounts of power will become common place as a desktop computer is today. This would mean PetaFLOPS (10^{15} floating point operations per second) machines that today require large rooms and kilowatts of power will be available at a desktop. This can be considered a continuation progress of computational power over the past 20 years into ever smaller, lower power packages, but nanotechnology will play an increasing role, not only for the electronics computation engine, but also for interconnects, cooling and packaging.

-- At least one 'supercomputer' that can perform 100 exaFLOPS, or 10^{20} floating point operations per second. This and related machines will be able to create simulation environments for designing and optimizing advanced aircraft with a fidelity rivaled only by actually building the system but with a turn around of hours rather than years.

(b) Molecular and Quantum Computers (Various Alternatives Proposed):
-- Interfaced with our traditional computing systems.
-- Early Quantum Information Technology (QuBits).
-- Architectures for scalable and secure quantum communications and computation.

(c) Nano-Computers:
-- It is unlikely that the nano-computers will replace existing, advanced technologies by then, but they should be available for specialized applications.

(d) Cognitive Computing:
-- Will be close to being able to do it in real time—although it's full fruition will still be a decade or two away.

(e) Optical Communication and Information Processing

(f) Smaller, Higher Density Storage (Various Alternatives Proposed):
-- >1,000X density increase
-- Systems able to store a billion-billion (10^18) bits in a cubic centimeter. Manufacturing costs for these systems will be under a dollar.
-- Continued development of advanced memory and storage devices are likely, many showing factors of 10X and greater capabilities.
-- Nanostructures will enable extremely low power, high density memory.

(g) Advanced Displays:
-- Continued development is likely showing factors of 10X and greater capabilities.

(h) Low-Power Nanoelectronics

(i) Non-Volatile Memory

(j) Enabling Technologies for Sub-Centimeter Vehicles:
-- Provide more flexible capabilities to identify and track moving targets in denied areas.

(k) New Materials:
-- Enable power generation, sensors, and secure communications.

(l) "Smart Dust" Systems:
-- At the small end of the scale, we will be able to build systems the size of a particle of dust that will have the capabilities of a laptop of today that will harvest energy from the environment.
-- Able to make some measurements of its surroundings, store data, process some information, and communicate with other dust particles or with a control station. This dust will be small enough to be ingested or inhaled without a person even knowing it. It could be used for tags, for information gathering, or for weapons.

(m) Molecular Self Assembly (i.e. Chemistry Engineered Toward an Outcome) and Mechanical Self Assembly (e.g. Fluidic Assembly of Micro/Nanoscale Parts):
-- Will have progressed toward application-specific successes to create, integrate and interconnect devices.

(n) Directed Assembly at the Micro/Nano Scale:
-- It is expected that prototypes of assembled systems of heterogeneous nanoscale devices will occur.

(o) Configurable and Reconfigurable IT Systems on Chip:
-- Relatively sophisticated prototypes expected.
-- Reconfigurable systems will benefit from advances in resistance change materials, where off/on resistance ratios of at least 10^5 and up to 10^7 are expected.

(p) Parallel Manipulation Systems for Nanoscale Assembly:

-- Lab demonstrations will be a reality.

(q) Electronic-Biological Convergence:

-- A rapidly growing area, presently represented by nano-bio interfaces, such as discrete chem./bio electronic sensors.

-- It is conceivable that a wide range of sensing (and actuating) systems will be demonstrated that spans the range of these interfaces, enabling the ability to "plug into" the electronic and biochemical systems of living systems.

-- Over the next decade, it is possible that we will see numerous sensor systems, with the key accomplishment being able to massively integrate and interface these to IT systems; with the following decade the demonstrations of interfacing to model biosystems.

(r) Nanobiosensor Technology

(s) Control and Guidance of Weapon Systems

(t) Ubiquitous Connectivity, Largely Wireless:

-- Will enable both allies and enemies to instantly know what is going on across the globe.

-- Will be enabled by advances in nano-structured materials for antennas and packaging. Advanced transistor structures will also be developed to deliver superior spectral efficiency for wireless communications.

-- Combined with extensive computational power, this will open a vulnerability to computer attack that will dwarf the security breaches occurring today.

(u) Hand-Held Platform Capabilities for Integrating Nano-Enabled Technologies:

-- Can easily integrate different types of small sensor and communication technologies. These platforms should employ faster and more secure technical solutions to improve the automation, integration, analysis and distribution of information to operational forces.

(v) Persistent Surveillance Capabilities:

-- To find, observe, and precisely target enemy capabilities in denied areas is possible.

-- Capability development would be required that pushes the state of the art to smaller scales in power generation and energy storage, sensors for tagging and tracking, new architectures for communication and information processing, and new materials to enable capabilities for the defense and intelligence communities.

(w) Small, Long-Life Micropower Sources

(x) Remote Creation, Harvesting and Storage of Energy

(y) Sources and Detectors at Either End of the Electromagnetic Spectrum

(z) New Approaches to Sensors for Chemical and Explosive Threat Detection

(aa) Sensing Platforms for Multiparameter Analysis of Biomolecules and Pathogens

(bb) Higher Efficiency Sensors for Radiation and Nuclear Material Detection

(cc) Single Photon Detectors

(dd) New Imagery Capabilities:

-- To identify and track moving ground targets in denied areas including investments in smaller form factor synthetic aperture radar and related radar capabilities.

(ee) Reduced Form Factor Radar-Responsive Tags

(ff) Anti-Tamper Technologies

(gg) New Methods for Audio Collection and Processing

What is your judgment of the potential of the various responses based on your knowledge and the supporting arguments presented? Focus on and discuss in

greater detail only those prospects you anticipate to be the major nanotechnology-enabled IT capabilities at or above TRL-6 by the year 2030.

Topic #4: The biggest challenges to overcome, obstacles to progress, in developing these nanotechnology capabilities for use in IT systems in the year 2030. *(Please read through the various, panelist responses synthesized below in blue font then answer the associated question at the bottom.)*

(a) Technology Transfer:
-- From lab bench to field—each element of the process is its own stovepipe
-- Bridging the gap from TRL 4 to TRL 7: identifying which clever ideas have the best chance of being fielded and then putting adequate resources to transition them from clever idea to demonstrated prototypes in relevant environments.
-- The US needs to integrate scientists, engineers, and customers into a more efficient cycle of technology development that brings recognition of new physics, design principles, qualification, and manufacturability all working together at earlier stages in the technology realization process.
-- Right now, scientists don't really understand how they can have an impact that could be fieldable and engineers don't always understand what clever design could be manufacturable. Bringing these groups together to value their respective strengths and identify what technologies could be based around largely unused nanoscale phenomena (i.e. Van der Waals forces, quantum mechanics, etc.) would create a new paradigm in nanotechnology and engineering.
-- Requires early, intense collaboration between research and development (R&D) and acquisition management teams; a justified statement of the ultimate users' needs (capabilities gaps); continuous improvement; commitment of the acquisition prime contractor; and, funding for the "Valley of Death."
-- To get low TRL level advances developed in universities and small companies across the "Valley of Death" to higher TRL levels. This may require increased government funding for selected applications.
-- Bringing technologies developed in the laboratories to the market. It took 50 years of work to bring the computer chip technology to this stage. Similar problems will be faced with molecular computing and other IT technologies.
(b) Manufacturing (Various Opinions Expressed):
-- It is extremely difficult to have a conversation about what manufactured products are possible (as opposed to the structures that have already been built), as almost all researchers are trained to reject feasible structures that cannot be manufactured by today's technology (or perhaps some modest extensions of today's technology). As a warm-up exercise, it is useful to examine some proposals that are clearly beyond today's technology. See, for example, Nanosystems (http://www.e-drexler.com/d/06/00/Nanosystems/toc.html) or some of the proposals by Nanorex (www.nanorex.com and click on "Gallery").
-- Systematic investigation of a wide range of structures that are inaccessible to today's experimental technologies can be pursued by computational modeling of molecular

structures. In other words, we know the laws of physics and we know how to model those laws on a computer. We can use computers to model the behavior of (say) a molecular switch even when we cannot yet build such a molecular switch. At least as important, if not more so, is the ability to model the manufacturing method for making the molecular switch. In essence, we can use massive computational power to let us examine today the manufacturing technologies of 2030—and by so doing can speed the development of these new technologies.

-- Our ability to fabricate materials and devices in the lab is relatively easy compared to our ability to manufacture complex, 3-D devices with the precision, reproducibility, and low-cost needed for a viable technology. Today, the necessary standards and reference materials needed to develop these manufacturing principles do not exist.

(c) Funding:

-- The biggest and most obvious challenge to overcome.

-- Don't believe that researchers are currently limited in good ideas. Rather, such long-term research, especially with an engineering systems bent, is resource limited.

-- The critical element is the ability of funding organizations to successfully identify and support the necessary high-payoff, long-term research.

(d) Training (Various Opinions Expressed):

-- One of the long-term implications of nanotechnology for engineers is that they are going to have to learn quantum mechanics, along with more chemistry.

-- Both graduate and undergraduate education should experience a gradual incorporation of these topics into the engineering disciplines.

-- The next generation of students to develop these nano/IT advancements in the US. I have no doubt that they will be developed, but I worry that they won't be developed first in the US. Right now, we are effectively killing off our youngest generation of professors in physical science and engineering—there is so little research funding available, that the youngest professors are not able to compete with those who have an established track record. If they don't get funded, they won't get tenure, or they will get discouraged and quit. If the young academic scientists and engineers of today quit, there won't be a next generation of students, since they won't see a future in science and engineering. If we lose our high quality academic research institutions, then it will be up to the Chinese and the Koreans to develop the nano/IT for 2030, and they will.

(e) IT Industry Challenges in Moving Along the Scaling Path:

-- These challenges are: (1) Power and Thermal Management; (2) Parallelism; (3) Complexity Management; (4) Security and Manageability; (5) Variability and Reliable Computing; and, (6) Communication (i.e. Interconnect).

-- Will run into the end of Moore's Law that came from simply continually miniaturizing what we currently do. However, computing power will continue to increase as common personal computers become more and more multiprocessor based. Also, new methods of computing based upon quantum and perhaps biological architectures will begin to be deployed.

(f) Handling Anticipated Higher Degree of Structural and Functional Variability:

-- In new device technologies that depart from CMOS.

-- Emerging nanoscale devices generally exhibit uncertainty in their behavior and have individual reliability issues. Most envisioned nanoprocessors are expected to utilize

nanometer-scale switches with performance limited more by nanoscale interconnect technology than by the active devices.

-- A challenge is laid out to develop new "nanoarchitectures" that are tolerant of defects and faults in the resultant circuits and systems and exhibit overall "black-box" system reliability. This may dictate a departure of the classical stored-program computer architecture that has held steady since the inception of modern computers.

(g) Integration and Fabrication:

-- Many present nano demonstrations tend to overlook or underestimate the need to then move to complex, integrated systems. Without integration capability, nano will be relegated to just discrete sensors and the underlying materials infrastructure.

-- New "nanoprocessor" systems are expected to be a heterogeneous mix of best-breed components.

-- Handling the complexity in fabricating these systems is a large challenge. Current nanoprocessor efforts for the most part side-skirt this issue of heterogeneity, but this cannot be put off for more than another 5-10 years.

(h) Various Novel Technical Approaches to Nanoscale Devices and Architectures:

-- Include quantum cellular automata (QCA), nanoscale neural networks, nanocells, biologically inspired electronic system structures such as the virus nanoblock (VNB), and hybrid CMOS-nanostructures and self-assembly.

-- The evolving nanodevices are still at the physics investigation stage (much as bipolar and CMOS were in 1960), so most practical engineering and manufacturing issues are yet to be discovered. This progress, and a weeding out of the device technologies can be expected with 20 more years of R&D; this process represents a daunting challenge and an enormous amount of work.

-- Each research camp will no doubt make arguments that their technology is best, but it is too early to make go/no-go decisions.

-- The history of modern electronics can teach lessons here, as competing silicon and GaAs bipolar technology has certain advantages, yet CMOS won convincingly in the 1980's due to the manufacturability and scalability of the integrated system.

(i) Implementing Devices and Interconnect at the Nanoscale:

-- Current techniques to wire up nanodevices are for the most part not manufacturable.

-- Self-assembly techniques where molecular chemistry plays a role to drive connections through energy minima, is a possible solution. Obtaining heterogeneity with self-assembly may prove extremely difficult.

-- Directed assembly at the nanoscale is worthy of attention, with a goal to continuously improve the ability to deterministically control "objects" at the nanoscale. The challenges in that case are harnessing and controlling various forces (e.g. Van der Waals forces, electrostatic) at the nanoscale, providing rotational degrees-of-freedom for manipulation, achieving nanoscale accuracy and repeatability, and achieving parallel throughput to make such assembly viable from a cost and time perspective.

-- Even after getting parts to where you want them is solved, making electrical contact to nanoscale devices is problematic. Due to the scaling, the contacts exhibit effects on the same order as the active device. Thus, a deep understanding of the entire device plus interconnect system is imperative.

(j) Developing Peripheral Products Needed to Support These Devices:

-- New packaging and heat transfer approaches are needed.

-- Better interconnects, as well as improved communications, are needed to get information to/from the nano-IT systems.
- Needed because the systems will be much smaller by 2030 and will have unique thermal management, packaging and interface problems.

(k) Standard Peer Review, or "Research by Committee," Process is Broken:

-- Unable to pursue research unless there is consensus in the research community that a particular research objective is both valuable and achievable. By the time every member of a committee thinks an idea is worth pursuing, the research is already out of date. And in today's competitive environment, serious dissent by one or two committee members is sufficient to block funding.

-- This, of course, assumes that the objective is to pursue long-term, high-payoff goals. Recent funding by, for example, the Defense Advanced Research Projects Agency (DARPA) is aimed at objectives well short of 2030, eliminating even the possibility of pursuing such research. Other funding organizations are also focused on shorter time periods.

-- This assessment suggests that the primary target of research should be the effectiveness of funding mechanisms. For example, we might modify National Science Foundation (NSF) peer reviewed research to involve review of funded research to see what succeeded, and correlation of the results with the evaluations of individual reviewers. If a reviewer forecast success, and the proposal subsequently produced successful results, the reviewer's opinion could be given greater weight in the next round of proposals. Financial or other incentives to individual reviewers based on some measure of success of the proposal would also be an area to pursue.

-- Market based forecasting and feedback schemes have been discussed for some time now, see for example: http://en.wikipedia.org/wiki/Prediction_market. Application of these ideas to research funding should be effective in improving the quality of funding for research—and the quality of the funding process is critical.

-- Systematic research on how to improve the effectiveness of research needs support sufficient to overcome opposition by those who benefit from the current state of affairs and who might as a consequence slow or block change. This is a real concern, as the author is personally aware of a research proposal to NSF aimed specifically at increasing the effectiveness of the peer review process that was withdrawn (rather than evaluated and rejected) following pressure on the submitter. Changing how research is funded can adversely affect existing beneficiaries of the system.

(l) Improving the Quality of the Funding Mechanisms

(m) Preconceptions:

-- The biggest technical challenge is envisioning the goal without limiting ourselves by our biases about what is possible. Computers are made from atoms, and our ability to make better computers depends ultimately on our ability to arrange atoms in precise and complex patterns. Thus, in forecasting future developments of nanotechnology for computers we must first ask what arrangements of atoms are possible and useful (without limiting ourselves to present-day manufacturing capabilities) and then ask what sort of manufacturing system would be able to produce the desired result.

-- The approach to computational chemistry and computer modeling is in contrast to today's approach, where computational methods are used to model structures that have either already been built or might soon be built. We need to deliberately abandon the

limitations of today's technology, and consider what the basic laws of physics permit. Such an examination, backed up by rigorous computational analysis, can provide us with insight into the new capabilities that could be available in a few decades time.

(n) Getting Stable Molecular Computers to Work:

-- Need those that are chemically stable for long periods of time and that are environmentally stable at various temperature/pressure/other environments.

(o) Getting Quantum Confinement Schemes to Work Reliably for Quantum Computers

(p) Memory Devices:

-- Right now, there are many new non-silicon approaches under serious commercial development. Phase change memory (PCM) should be introduced to the market shortly. Magnetic random access memory (MRAM) is available from Freescale. Both devices appear shrinkable to 10 nm dimensions.

-- The obstacles are those that face any new product on the market. These new memories must compete in the marketplace with the established silicon memory devices. PCM is expected to eventually win in the non-volatile (Flash) memory market (cell phone, cameras, etc.) because the further miniaturization of silicon, non-volatile memory is believed to be very limited.

(q) Control and Reproducibility of Nano-Scale Structures:

-- New manufacturing techniques will be needed to deliver sub-10 nm structures.

(r) Power Generation and Storage:

-- Fundamental challenge to realizing ubiquitous computing and connectivity. As a nation we are becoming critically dependent on foreign sources of energy. If we do not have sufficient power, others can catch or exceed our nation's capabilities in all areas.

(s) Thermal Issues:

-- The new technologies, and the continual miniaturization of what we have now, will continue to have increasing thermal issues that will need to be addressed.

What is your judgment of the potential of the various responses based on your knowledge and the supporting arguments presented? Focus on and discuss in greater detail only those prospects you regard as the biggest challenges to overcome to develop these nanotechnology capabilities for use in IT systems in the year 2030.

Topic #5: The impacts nanotechnology in the realm of IT will have on the world in 2030. *(Please read through the various, panelist responses synthesized below in blue font then answer the associated question at the bottom.)*

General Comments:

-- The devices of digital information technology are: Logic (switches), Memory, Interconnections (wires, waveguides) Transducers (sensors and other input and output devices), and Energy Supply (batteries). Nanotechnology will improve all of the attributes of all of these devices. All will be available in the consumer marketplace built into a wide variety of consumer products.

-- The world today has been transformed by IT in many ways over the past 25 years—think of how much more powerful computers are and all of the new things that exist today—a cell phone that is a camera that is a personal digital assistant. The types of changes that have occurred in the past 25 years will occur in the next 25 years. In general, the world will be both much more efficient and it will be much more difficult to keep a secret.

(a) Improved Communications and Connectedness—Better and Faster:

-- Everyone will be 'connected' via commercially available products. Our way of life will be highly dependent on portable electronics and IT. Militarily, nanotechnology and IT will create smart networks, provide instantaneous information (and knowledge), persistent surveillance and situation awareness, etc.

-- We will be able to access the internet at much greater speeds than we do today. Information of all kinds will be at our fingertips. More tasks will be done on-line, e.g., more banking, buying/selling, etc.

-- Communications bandwidths will be much higher.

(b) Vastly Cheaper Memory

(c) Much Faster and More Power-Efficient Processors

(d) Small, Cheap Sensors:

-- Think of an artificial fly that can record audio and video and then transmit that information in a secure manner to a host.

-- Can be widely distributed in the environment to gather, analysis and distribution information.

(e) Intelligent Systems:

-- As computational power increases and size decreases, we will add intelligence to almost everything. Obvious military applications are smart weapons – smart bullets with the power of today's super computers, for example. The terse answer "better computers" does not do justice to the possibilities.

(f) Improved Encryption/Decryption Capabilities

(g) Improvement of Materials:

-- Such as quantum dots for low power lasers, and membranes for fuel cells.

(h) Electronic-Bio Sensors and Systems:

-- Have the potential for tremendous impact if integration complexity (with fidelity) can be achieved.

-- Applications include the interfacing of biosensor systems to electronics (human for obvious applications; animal and insect for distributed sensor systems), security (DNA and biochemical identification), and potentially enabling blue-sky biomolecular computing.

(i) More Information Readily Available to Almost Everyone Worldwide:

-- For example, our medical information whenever and wherever we need it.

-- Each of us will have an overwhelming amount of information available to us, and most of those advancements will be because of nanotechnology.

(j) New Business Models:

-- With faster information flow, IT-based nanotechnology will enable more people to work remotely and thereby affect business's financial situations.

-- IT-based nanotechnology will make it easier to do product development from multiple companies, multiple places anywhere in the world (i.e., the world will be getting flatter). This could affect global trade and our relationships with other countries.

-- Will create new capabilities that also will permit the development of new business models and new capabilities by small groups of individuals (Will people be able to create sophisticated individualized medical devices, for example?).

(k) New Security Threats:

-- Individuals may be able to create the equivalent of hardware viruses and worms that bring down large scale systems.

(l) Unimagined, Revolutionary Applications:

-- If the miniaturization of IT devices continues with the invention of new devices to replace the transistor for information processing and memory, then the cost-performance of IT systems will still be improving at current rates or greater. Historically, the important applications of ever-cheaper IT have always surprised us. I cannot imagine the important new applications of IT in 2030 if cost-performance is, say, 100,000 times better than it is today.

-- New physics, design principles, qualification, and manufacturability all working together at earlier stages in the technology realization process. Bringing scientists and engineers together to value their respective strengths and identify what technologies could be based around largely unused nanoscale phenomena (Van der Waals forces, quantum mechanics, etc.) would create a new paradigm in nanotechnology and engineering.

(m) "Software-esk" Development Cycle:

-- The development of nanotechnology will in some sense follow a parallel path to that we saw in IT capabilities in software only this time in hardware. It took an enormous investment of time, people and money to develop the software infrastructure we have today. Once developed however, this infrastructure allowed individuals to perform tasks of tremendous impact (positive or negative) that once could only be developed by teams of individuals. For example, a small number of people could write software that enabled completely new business models (e-Bay, Amazon, etc.) and that relied on the IT infrastructure already in place. At the same time individuals could also write viruses and worms that could do tremendous damage to that same infrastructure.

(n) Human Health

(o) Control Over Weapon Systems

What is your judgment of the potential of the various responses based on your knowledge and the supporting arguments presented? Focus on and discuss in greater detail only those prospects you regard as the major impacts IT-based nanotechnology will have on the world in 2030.

Topic #6: The potential, "technology surprises" anticipated with IT-based nanotechnology in 2030 resulting from the forces of globalization and commercialization. *[A technology surprise is defined as a technological development that could undermine*

US military preeminence.] (Please read through the various, panelist responses synthesized below in blue font then answer the associated question at the bottom.)

General Comments:

-- We won't own all the clever nanotechnology ideas, and moreover we won't bring most of them to market.

-- "Technology surprises" are not likely to *directly* undermine US military preeminence. Presumably the US will continue to be a leader in the use of new technologies for military purposes. However, I think that ever cheaper and more pervasive IT (which includes communications technology) will make it ever more difficult to determine who the enemy is and where the enemy is. That seems to be the current path for international terrorism.

-- The US has broad-based research funding in all the critical areas, although many researchers are constrained by application focus. "Surprises" will occur from unanticipated exploratory areas, and the decreasing amount of curiosity-driven research in the US has a deleterious effect on being competitive in these areas.

(a) Implications of Overseas Microelectronics Outsourcing:

-- An area of concern which potentially has impact on security by "unreliable chips" (i.e., hidden Trojans), and potential superiority in NVRAM.

-- Corruption of our sources of microelectronics could bring the US unforeseen problems. Historically the US military has relied on captive, or at least on-shore, integrated circuit (IC) foundries. Growing capital costs and changes in market demographics is shifting a large fraction of the IC business off-shore. In addition, the traditional US Defense contractors can not afford to maintain low-volume foundries to supply chips to the Department of Defense (DoD). Both of these trends put the trustworthiness of microchip fabrication outside of government control, at risk. If the microchips in defense systems are compromised, the foundation of our national defense is at risk.

(b) Another Country(ies) Overtakes US as Technology Lead:

-- Within this timeframe it is expected that nations in the Pacific region will become (if they are not already) the preeminent manufactures in the world and in fact the US will be buying most of its IT technology from there. And so it follows from this that indeed the US military may no longer be the predominant IT–based force in the world.

-- If other countries become more innovative than we are and are first to invent the new nano/IT. The primary country that I think of in this respect is China. I was in a meeting in Japan a few years ago, and one of the Chinese representatives at that meeting boasted that there were 30,000 young Chinese studying nanotechnology related subjects (I would guess that the number in the US is more like 3,000). This may have been an exaggeration, but any international conference I attend now seems to have as many Chinese attending as Americans and Europeans. I see more and more papers from China in the journals, and they are getting better in quality. The Chinese are benchmarking our educational system, and they are slowly but surely making improvements and catching up.

-- Waking up after a couple of decades of complacency and neglect of our research infrastructure and finding out that we are being outclassed.

(c) Self-Replicating Weapons Systems:

-- Biggest potential "technology surprise" that might undermine US power. For a recent review of self replicating systems, see http://www.molecularassembler.com/KSRM.htm. Various scenarios involving artificial self replicating systems are reviewed in http://www.foresight.org/nano/Ecophagy.html (generally referred to as "gray goo" scenarios).

-- Existing biological replicating systems demonstrate feasibility. Artificial replicating systems with enhanced capabilities seem entirely feasible. Research in this area is grossly underfunded when considered in the context of either its remarkable economic value or the potential risks. Note that when evaluating risks, a small probability of successful implementation of a novel WMD poses an unacceptable risk to national security.

(d) Controlled, Light-Weight, More Powerful Warheads:

-- May pose danger to US military if they are in wrong hand or developed by other countries.

(e) Communications and Computing Technology Based on Quantum Information Science Maturation:

-- This field exploits physical quantum effects at the atomic scale that theorists predict can lead to many orders of magnitude improvements in specialized computing and extremely secure encrypted communications. The threat relates to the ability to rapidly perform specialized data searches over a million times faster than is possible today. This could compromise some militarily critical capabilities.

(f) Information Gathering and Decryption Breakthroughs:

-- The amount and complexity of information gathering against us could increase considerably as a result of nanotechnologies being developed and produced world wide. Distributed, autonomous units could collect information and distribute that information at infrequent intervals such that there is a low probability of detecting or defeating the unit.

(g) Portable Computer Capabilities:

-- Could be used to attack US networks and infrastructure.

(h) Harvesting and Production of Both Energy and Water:

-- The US may focus solely on what it takes to produce large amounts of energy for a large force while adversaries may control the ability to create and/or harvest small amounts of energy at point of use for distributed units (units may be man or machine).

(i) New, Small-Group Business Models and Capabilities

(j) "New-Wave" Attack Capabilities—e.g. Cyber Attack, Hardware Viruses and Worms:

-- Our whole IT infrastructure may at some point be in jeopardy. As an example, our military systems may be subject to cyber attack. An instantiation of this would be our information coming from satellites being disrupted. Or, our power systems could be immobilized. We could become much more vulnerable than we are today.

-- Capable of bringing down large-scale systems.

What is your judgment of the potential of the various responses based on your knowledge and the supporting arguments presented? Focus on and discuss in greater detail only those prospects you anticipate as the major "technology surprises" from IT-based nanotechnology in 2030 resulting from the forces of globalization and commercialization.

Topic #7: The threats envisioned to come from terrorists combining nano- and information technologies in new and dangerous ways that will impact the USAF mission in 2030 and beyond. *[Considering the two facts that have emerged from the current Global War on Terror—this is going to be a long, "Cold War-like" conflict and our adversaries are very technologically savvy.] (Please read through the various, panelist responses synthesized below in blue font then answer the associated question at the bottom.)*

General Comments:
-- Nanotechnologies can be developed or used by relatively low technology groups or countries, giving some of our adversaries' access to more modern technology than they have had in the past. This fact can change the military playing field dramatically.
-- The battle is on—they will try to use nano- and information technology to understand our societal and military vulnerabilities better (and faster) than we do, while we are trying to do the same in understanding their vulnerabilities. The key difference is that we are a visible target and they are not fully visible. Therefore, we have greater need to also create information tagging and tracking technologies (both nano and non-nano) which can identify who is the adversary, with precision and proof in the identification process.
-- Although there are significant threats from nano (e.g., toxic nanoparticles) and from IT (e.g., information security), IT-nano requires massive, visible investment, so threats seem minimal.
-- I do not see a "new and dangerous way" in which terrorists will combine nano- and information technologies.
-- A lot of nanotechnology work is done using beaker chemistry and does not require many resources. Combination of nanotechnology and IT may be dangerous.

(a) Cyberattacks on US IT Systems and Critical (Computer-Controlled) Infrastructures:
-- Cyber-terrorism threatens to undermine the internet for commerce and military applications. As the US becomes ever more dependent on internet connectivity this vulnerability could be exploited.

(b) Infiltration of US Command, Control, Communications, Computers, and Intelligence (C4I) Networks

(c) Encryption Capabilities:
-- Able to thwart US surveillance and information-gathering approaches making America's defenses less effective and also making it harder for the US to track terrorist actions.

(d) Sophisticated Jamming and Counter-Surveillance Technologies

(e) Improved Intelligence-Gathering Capabilities:
-- More IT capabilities bring with them increased security risks on our end. Terrorists may have more opportunities to gather intelligence information on the US armed forces giving them a better advantage than they have today.
-- Ability to track our forces taking away some of our military advantage.

(f) Intelligent Reasoning Devices:

-- Will be coming online, and will be available to all.

(g) Self-Replicating Weapons Systems—Biological or Artificial:

-- Could be manufactured in small facilities (particularly when compared with the large facilities required for nuclear weapons), would be easy to disperse, and difficult to monitor.

(h) Small, Autonomous Vehicles for Intelligence Gathering and Direct Attack:

-- It will be possible to buy commercial IT products with the capability of making autonomous vehicles of sorts – rather than worry about something large one could make a lot of small things – like artificial rats or bats. These could be programmed to infiltrate a wide variety of installations for either intelligence gathering or for direct terrorist activity, like releasing a toxin, etc. A relatively small country or well-funded organization could set up a factory and mass manufacture thousands or even hundreds of thousands of such rats or bats—or they might just buy existing toys and modify them for their own use. These could be used to overwhelm the defenses of an installation. The issue here is that inexpensive technology can be used to asymmetrically attack the US and US interests, and that trying to defend against this small stuff could be extremely expensive. We are going to have to have even more advanced technologies to combat these types of terrorist threats.

(i) Improved Communications Capabilities:

-- Anyone who is interested should have instant global communications, and the ability to coordinate actions across large areas. Huge amounts of current information beyond just weather should be available to all.

(j) Continued Use of New or Improved Consumer Products:

-- As they use cell phones and computers today.

-- If information, made more globally available through application of nanotechnology to IT, is used for purposes other than those intended, we could see terrorists or other threats using modern technologies against us.

(k) Foundry-Made Unreliable Chips or Hardware Components

(l) Hardware Viruses and Worms:

-- Capable of bringing down large-scale systems.

(m) New, Small-Group Business Models and Capabilities

(n) Increased Chemical Threats:

-- At the same time the US is developing countermeasures such as taggants to help mitigate this threat.

What is your judgment of the potential of the various responses based on your knowledge and the supporting arguments presented? Focus on and discuss in greater detail only those prospects you regard as the major threats envisioned to come from terrorists combining nano- and information technologies in new and dangerous ways that will impact the USAF mission in 2030 and beyond.

Section C. Proper Sector Roles and Responsibilities – Defense versus Commercial

Topic #8: The areas of nanotechnology R&D relevant to future IT capabilities envisioned to be driven by the commercial sector and global marketplace. *(Please read through the various, panelist responses synthesized below in blue font then answer the associated question at the bottom.)*

General Comments:

-- The global market place tends towards unregulated delivery of IT infrastructure. Such an open approach is unlikely to be consistent with the USAF and DoD needs. The commercial market will drive technology performance and reductions in cost.

(a) Nanodevices to Solve Predicted Bottlenecks with Scaling Reduction:

-- The commercial sector will continue to drive Moore's Law. As they reach the limit on traditional silicon manufacturing processes, they will likely turn to various forms of nanotechnology to keep this trend progressing. Areas for exploration include quantum computing and molecular computing, both working on length scales much smaller than the scales currently in use in today's computers. This research will give us smaller, faster processors.

-- The commercial sector will continue the drive to "smaller, faster, cheaper" devices for IT. The drive for smaller and faster transistors for information processing is nearing its end, but R&D in search of newer devices, suited for further miniaturization, is gathering momentum.

(b) NVRAM and Other High-Density Memory:

-- The IBM Millipede project is aimed at mass storage using an array of Scanning Probe Microscopes (SPM). Evolutionary improvements of such a device would push resolution of the SPMs to finer and finer feature sizes, ultimately driving research towards molecularly precise modifications of surfaces.

--The use of CNTs for NVRAM (see, for example, proposals by Nantero) is another area where current research offers the possibility of high-density memory and evolutionary improvements would push manufacturing technology closer to fundamental limits.

-- There is already enormous commercial R&D activity in new non-volatile memory devices which will compete in the most rapidly growing piece of the entire memory and data storage market.

(c) Continued Doubling in Performance (Price, Speed, Size) of Semiconductor Chips Every 18 - 24 Months [i.e. Moore's Law]:

-- The global market will drive to keep the rate of progress in IT at its traditional Moore's Law rates. This is because the entire infrastructure is based on the fact that old IT systems become obsolete in three years and need to be replaced. Nanotechnology will be the key factor in being able to achieve these goals.

(d) Larger, Faster Memory Devices

(e) Faster, Denser Data Storage

(f) Telecommunications:

-- It is estimated that currently the world-wide expenditures on telecommunications is $2 trillion. And so, from this it is clear that this area of technology is driven by the commercial sector and that will continue.

(g) Advanced Sensors:

-- For first responders and protection/detection of public places with a focus on low probability of error. (These will not require greatly autonomous systems and so may not require nanotechnology.)
-- There is a lot of development of biosensor technology being driven by commercial interests in health care and medicine.

(h) Nanoelectronics Components and Devices:
-- Will find widespread application in consumer electronics including computers, audio and imaging systems. Many of these systems will be highly integrated. For example, you can hardly buy a cell phone today without a camera. Future devices will be more integrated, extremely powerful, and less conspicuous.

(i) Heterogeneity in IT Platforms:
-- By 2020—Driven by the need to create new capabilities and market opportunities, especially individualization of systems, as conventional CMOS scaling (and with it, the brute-force performance improvements) runs out of steam.

(j) Electronic-Biological Convergence:
-- The diagnostic, point-of-care, and medical applications will fiercely drive the underlying technology, albeit with a medical focus. This foundation will quickly enable the extensions into security and bio-electronic interfaces.

(k) Lighter, More Compact Computer Displays

(l) Smaller, Better Communication Devices

(m) Micropower Sources:
-- Smaller, more efficient energy sources.

(n) Optical and Audible Communications

(o) Logic Circuits for Decision Making

(p) Bioinformatics:
-- A major area that can be driven by commercial sector and global marketplace.

What is your judgment of the potential of the various responses based on your knowledge and the supporting arguments presented? Focus on and discuss in greater detail only those prospects you envision as the major areas of nanotechnology R&D relevant to future IT capabilities that will be driven by the commercial sector and global marketplace.

Topic #9: The USAF mission elements most impacted in 2030 by advances in nanotechnology in IT. *(Please read through the various, panelist responses synthesized below in blue font then answer the associated question at the bottom.)*

General Comments:
-- The question is difficult to answer because of the significant probability of pervasive change in many of the underlying assumptions. As one example, extrapolation of present trends in computer power suggest that by 2030 we will have hardware as computationally powerful as the human brain. If software advances can take advantage of this capability, systems able to outthink humans on the battlefield will be available. This shift will change how we recruit, train, and deploy the remaining human elements of the USAF.

-- Capabilities once thought of as expensive and only available to large organizations (USAF) will be available to anyone with a few dollars. These could include advanced radar, and multifunctional materials with embedded electronic sensor systems.
-- By 2030, one may expect a significant degree of maturation of nano-device scaling within IT systems. The unknown is which specific technologies will be winners and which are dead-ends.
-- The ability to understand, control, and manufacture microelectronics will continue to be a foundation of our national security. This is especially true for the Air Force, whose high performance fighters, for example, can only be flown under computer control.

(a) Smaller, Autonomous Vehicles:

-- Miniaturization and multifunctional materials with embedded electronic sensor systems will lighten aircraft and lead to more sophisticated generations of micro- (maybe nano-?) air vehicles.
-- The advances in computation power and communications will also enable highly adaptable, robust, unmanned systems. This will remove the pilot from many current missions; however, verification and security vulnerabilities in computer hardware and software will need to be addressed.

(b) Ability to Replace Pilots with Automated and/or Remote-Pilot-Assist Systems:

-- This trend is already evident, but the capabilities of the supporting IT systems will be greatly enhanced by continuing developments in IT hardware.
-- The IT advances of the next 25 years will enable a revolution in aircraft and systems. By taking the pilot out of the airplane, the power to mass ratio will be much larger, the volume of the aircraft will be much smaller, the speeds and accelerations will be much larger, and the radar cross section will be much smaller. The airplanes really will fly themselves – their operators will give general directions and receive confirmations of orders and missions accomplished.

(c) Remote Sensing:

-- The impact of this technology will be both positive and negative. The USAF will have the ability to monitor virtually the whole world in real time. However, our adversaries will also have, in part, the ability to monitor us. Because there is only one superpower- much of the world may feel that we are their adversary.
-- Low-cost massively distributed sensors (in addition to a conventional embodiment, a blue-sky idea is animal (or insect)/electronic hybrids, utilizing biopower for mobility, system power, and communication) will impact personnel/facility security and surveillance.
-- Might be done by swarms of sensors, whether from many, small satellites, from swarms of radar systems, or other reconfigurable sensor systems. Taken globally, this could result in a worldwide sensor web. Improvements in on-board computing of these systems may be able to process the data on-the-fly and provide more information, rather than lots of data that needs to be processed, to the end user.

(d) Command and Control:

-- The Air Force will have a huge number of unmanned aerial vehicles and the information gathered by them will need to be semi-automatically collected and evaluated, and prioritized. IT will play major role here.

(e) Better Military Planning

(f) Air and Space De-confliction

(g) Controlled and Guided Munitions Systems
(h) More Accurate Guidance Systems
(i) Air Delivery Systems:
-- Augment capabilities and performance, but not necessarily change it
(j) Space-Based Systems:
-- Spacecraft capable of on-board decisions.
-- Impacted by the fact that nanotechnologies are smaller and lighter, and therefore reduced cost of deploying systems
-- New nanoscale phenomena exploited to permit decreased need for cooling or shielding, thereby reducing deployment cost
(k) Cyberspace:
-- The growing US dependence electronics and IT devices creates vulnerabilities from adversaries that will have IT technologies as capable as ours causing an endless duel of counter-countermeasures.
(l) Fundamental Changes in Manufacturing Technology:
-- Greater precision, greater flexibility, lower cost, and more rapid manufacturing.
(m) IT Infrastructure Verification and Security Issues:
-- The USAF, and the DoD in general, will need to address these issues specific to their mission. The ability to access trustworthy hardware and software will be essential.
(n) Information Dominance:
-- One can envision better, information reaching the commanders, pilots, etc. faster, the result of nanotechnologies applied to processors and the shrinking of conventional devices such as sensors.
(o) More Capable Surveillance
(p) Improved Target Tracking and Identification
(q) Progress in the Cognitive Sciences:
-- Nanotech-improved IT systems may also enable capabilities such as super-human artificial intelligence which may offer advances in human-machine interfaces, more automated flight control systems, etc.
(r) Faster, More Efficient Scheduling of Assets
(s) More Responsive Anti-Jam Capabilities
(t) Military Encryption/Decryption:
- Quantum information processing may be a step to greater decryption capabilities, and it may be based in nanotechnology.
(u) Algorithms for Pattern Recognition
-- Largely independent of developments in nanotechnology, the gradually improving understanding of the algorithms for pattern recognition in the brains of humans and other organisms may, by 2030, allows the implementation of pattern recognition (i.e. target acquisition) software and hardware solutions that are superior to the best human capabilities.
(v) Molecular Computing

What is your judgment of the potential of the various responses based on your knowledge and the supporting arguments presented? Focus on and discuss in greater detail only those USAF mission elements you regard as the most impacted in 2030 by advances in nanotechnology in IT.

Topic #10: The policy issues senior USAF leaders should tackle to enable the full potential of nanotechnology-enabled IT capabilities in 2030. *(Please read through the various, panelist responses synthesized below in blue font then answer the associated question at the bottom.)*

General Comments:

-- Pick a few areas and invest enough resources.

(a) Allowable Level of Autonomous Decision Making to Produce a Given Effect:

-- Greater levels of autonomy could lead to a more responsive strike force, but could also end up contradicting intended policy, inadvertently. Greater levels of autonomy will require more nano-enabled technologies in information gathering, analysis of information, communication, decryption, encryption, and distribution of information-gathering systems.

(b) Facilitate Desired Mission Model:

-- The USAF is interested in focusing on the real-time acquisition of data, turning that data into information, and based on that information reaching decisions for developing courses of action. We need to be able to take these courses of action and simulate the effects of following each of these courses, to arrive at what is the best course of action to take. Policies must play a part in arriving at this best course. This analysis is in fact a cognitive approach, which will be possible with the advancements that are expected through the advancements in computing power in this time frame.

(c) Create New R&D Organization:

-- Specifically focused on long-term, high-payoff research. This should include research into more effective methods of funding research ("meta research") as well as research focused on the fundamental limits of manufacturing—limits that are likely to be approached very closely by future manufacturing systems, particularly including the manufacturing systems required to make future molecular computers.

(d) Reinstate DARPA's Advanced Research Mission:

-- Get DARPA back into doing advanced research, instead of incremental improvements with 18-month timelines.

(e) Dependence on Foreign Electronics and IT Services:

-- Globalization does not provide the US with trusted foundries and secure technologies.

(f) Promote Environmental Conditions to Grow Technology Workforce:

-- USAF needs will be met by specific and unique applications of the general IT that will be developed. To this end, the USAF and their suppliers will have to have people educated in how to utilize the technology to build the autonomous aircraft, etc. It makes sense that such work should be done in the US by American citizens. If the US does not step up and create the environment necessary for people to thrive in IT careers, there won't be any American citizens who can do such jobs. What do we do then—contract the work out to China?

-- Foreign governments are reaching out to multinational companies to convince them to do more of their manufacturing and R&D in their countries. In responding to their shareholders, the companies are allocating their assets where they can achieve the largest

returns on their investments. More and more, this means moving over seas—not because things are cheaper there, because when looking at all the costs, they are not. It is because that is increasingly where the infrastructure and the talented people are. It is entirely possible that many of the large multinationals could become effectively Chinese or Indian-based companies if current trends continue.

(g) Support for Emerging Manufacturing Technologies:

-- Key micro/nanofabrication IT technologies are offshore, which remains a strategic concern. This will not stop, but can be mitigated through greater support in the U.S. for emerging manufacturing technologies (e.g. micro/nano scale assembly) that may provide a strategic advantage. Perhaps more important, such manufacturing support should be then allowed to be leveraged by researchers to accelerate inroads into systems integration.

-- While computers are the most obvious example, a wide range of products would benefit from manufacturing techniques that provide low-cost manufacturing with molecular precision.

(h) Research Advocacy:

-- The USAF should advocate for and sponsor continued research in advanced IT technology (electronics, communications, software) both within the Air Force and across the US to insure the USAF and the country has access to the top scientist and engineers along with the resulting technology. We should not allow our country to become second tier in any of the critical IT areas so we can maintain our military and commercial strengths.

-- Absolutely push our government to fund physical science, math and engineering education and research at appropriate levels—at this stage that means quadrupling the 6.1 (basic research) budgets of the services, NSF and Department of Energy basic science over the next decade. The cuts in 6.1 funding for universities is devastating our engineering schools—this is really the most important investment our military can make in our future.

(i) Increased R&D Focus on Development of Integrated Systems:

-- Instead of discrete device demonstrations, increase R&D focus is necessary on this major impediment and establish of longer-term stable research funding to target this.

(j) New Verification Policies:

- The USAF should acknowledge the vulnerabilities in computer hardware and software and put policies in place to make verification, or at least risk reduction, the responsibility of system developers.

(k) Facilitate Collaboration Between Defense Companies and Nano-IT Development Organizations:

-- Make it easier for defense companies to work with the sources of the nano-IT development organizations. For example, intellectual property (IP) issues are extremely prevalent in the nanotechnology world especially with universities, and these could slow down getting technologies from the lab into military systems. This would need to be done with some kind of legislation that makes for a fairer treatment of IP between companies and universities especially when the company is funding the R&D.

(l) Improve Commercial Off the Shelf (COTS) Product Usage:

-- Tackle the issue of how to harden or customize "civilian" IT systems for military applications. Focus on redundancy and error correction and recovery (cheap, plentiful

throw-away components) to achieve needed reliability, rather than very expensive components with individual reliability that is very high.

(m) Technology Transfer:

- Transitioning new ideas to application—very big "Valley of Death" between science/discovery and technology/application. More exploratory funding is needed to bridge this gap.

- Can't stop this development . . . can drive it, accelerate it and stay ahead of adversaries in what you understand and can create and deploy . . . means having strong support for open research closely coupled to internal development and deployment.

(n) Study Effect of Nanomaterials on Environment

What is your judgment of the potential of the various responses based on your knowledge and the supporting arguments presented? Focus on and discuss in greater detail only those prospects you regard as the major policy issues senior USAF leaders should tackle to allow the full potential of nanotechnology-enabled IT capabilities in 2030 to be achieved.

Topic #11: The best, USAF investments in nanoscience and nanotechnology to enable IT capabilities that perform its mission in the year 2030. *(Please read through the various, panelist responses synthesized below in blue font then answer the associated question at the bottom.)*

(Potential Considerations Derived from Questionnaire #1)

General Comments:

-- The global market will drive ubiquity and high production volumes. The USAF will naturally want the opposite—exclusivity. Partnering with owners of "trusted foundry" capabilities on custom design of integrated circuits for specialized military applications is a cost-effective way to put exclusive capabilities in military IT systems.

-- Working on devices (nanotechnology) will not be effective unless the military can invest at a level comparable to the billions of dollars a year spent by each of the major semiconductor manufacturers just to stay competitive.

(a) Integration:

-- Of various nanotechnologies into monolithic platforms for specific military needs.

(b) Security Capabilities:

-- IT-nano has a huge potential to combat terror—specifically, security as applied to hardware (e.g., the encoding of hard-wires security codes in electronics), goods (e.g., sensors to detect contamination), and personnel (e.g., DNA and biochemical tags for friend/foe, at a distance; and low-cost, distributable explosive sniffers).

(c) Research into Nanotechnology-Based Weapons Systems (e.g., Self-Replicating Weapons):

-- It is unlikely that commercial organizations will fund. As a consequence, direct funding of this area by some appropriate governmental funding agency will be required.

(d) Advanced, Autonomous Sensor Systems Development:

- The military would benefit from commercial advanced sensor development but would also need to focus on more autonomous sensor systems that may require greater sensitivity per detector, with greater false positives, but more redundancy in sensor to check for false positives.

(e) Advancing New Forms of Computing—Quantum and/or Molecular Computing

-- Dr. Jim Tour at Rice University is working on a molecular computer based on a randomly assembled collection of active molecular electronics molecules in very small areas comprising Nanocells. Each of the Nanocells can be programmed to work as AND, NAND, and other logic devices. What is still needed for this system is a programmable Nanocell in a commercially viable package.

(f) Enhance Technology Transfer Process:

-- Better bridge gap from TRL 4 to TRL 7—between the lab bench and field

(g) Greater Basic Research Budget

(h) Replicating Systems Research:

-- Biological replicating systems demonstrate feasibility. Artificial replicating systems with enhanced capabilities seem entirely feasible.

What is your judgment of the potential of the various derived responses based on your knowledge and the supporting arguments presented? Focus on and discuss in greater detail only those prospects you regard as the best USAF investments in nanoscience and nanotechnology to enable IT capabilities that optimize its mission in the year 2030. ***[Please give this question extra consideration as it is the core of this USAF research effort. Don't feel free constrained to only assessing the previous responses if you have additional inputs.]***

Section D. Additional Considerations—Panelist-Derived Questions

1.) Not everything needs to be nanotechnology to achieve a stated goal. What areas does the US not need to pursue with nanotechnology because other solutions are adequate? Is the US ahead in those areas or is that technology driven by a global market?

2.) The global market needs pretty much parallel what is going on in the US. It is dangerous to assume, and incorrect, that innovation will only take place in the US and that the only thing we should do is close off from the rest of the world. The technologically savvy countries in the world continue to close the gap with the U.S. in research. In fact, many countries are taking on a strategic focus with large investments in education to improve their ability to innovate, modeling the success of the US educational system. How should the USAF take advantage of developments that will inevitably occur outside the US (in China, Taiwan, Japan, India, etc.) and turn them into a comparative benefit for the USAF?

3.) A considerable amount of fundamental R&D in nanotechnology that could be applied to IT is taking place in academic institutions. How can we promote academia's continued R&D in IT-based nanotechnology yet preserve US information dominance?

APPENDIX 3: CONSOLIDATED QUESTIONNAIRE RESPONSE DATA

USAF "Blue Horizons" Research Program
Summary Data Collected from Delphi Questionnaires #1 and #2

(NOTE: Panelist responses to Questionnaire #1 synthesized below in blue font; responses to Questionnaire #2, in red)

General Comments:
-- There is a lot of spin in this document, which is a big problem in general facing R&D spending.
-- The definition of nanotechnology seems to differ among panelist – some seem to define it as one dimension on the nanoscale. I define it differently – all 3 dimensions on the nanometer scale. This affects the comments made.
-- The vast majority of comments made in response to the first questionnaire are very good and valid. There were a few comments that I felt were completely out of line, and in those cases I have provided a rebuttal.

Section B. "The Art of the Possible" – Nanotechnology's Contribution to IT in 2030

Topic #1: The important advancements and trends shaping today's nanotechnology in IT development roadmap.
General Comments:
-- The responses provide a good overview of the capabilities that are expected – better computers (using a range of metrics) are going to be available over the coming decades pretty much independently of Air Force funding.
-- I think that all of the responses are valid and important contributors to the "art of the possible". If this could be pulled together into a few coherent pages of prose, it would be a fantastic introduction to the field of nano-driven IT.
-- In my opinion the most important advancements and trend are in the combination of three areas: Increased information access speed + modularity + distributed information gathering and decision making. Couple this together with greater cross-department operations (e.g., USAF + Army) and this creates a more responsive force to deal with threats. An important technological part of this equation not mentioned above is the use of unmanned aerial vehicles (UAV) of all types to gather information (with embedded sensor systems). In the near future these can be smaller, and their on-board data processing will be greater. Hence modularity, distributed information gathering and possibly even decision making could be done by groups of UAVs.

(Important Advancements)
(a) Microelectronics—Now Nanoelectronics
-- Microelectronics has clearly penetrated the nanotech scale.
-- Microelectronics as we know it today with will not continue to progress in the same way out to 2030. Improvements will be driven by new insights in material and circuit architectures. The ability to exploit research breakthroughs will lead to a fundamental military and commercial advantage.

(b) Optoelectronics

(c) Mechanical Microsystems—Now Nanosystems

(d) New Algorithms for Data Analysis:

-- Big area

(e) Instrumentation and Tools:

-- Capable of nanoscale imaging, characterization, fabrication, and manipulation.

--Developed originally for microsystems, have evolved into critical tools for nanoelectronics.

(f) Lithography:

-- IT systems demand complexity, only possible through the integration enabled by parallel processing.

-- Although next generation lithography systems are tremendously complex and expensive, viable alternatives have not been identified to create useful integrated systems. (While I know this is strictly true, some new lithographic capabilities have been identified and exercised, such as interferometric lithography [ref: S. R. J. Brueck, Microelectron. Eng. **42**, 145 (1998)]. These will need to be further developed for commercial grade use, but they show great promise. One of the barriers to utilizing such technologies is that new methods of circuit layout/design should be developed to fully utilize the benefits of new technologies and this is an area of potential investment to help keep the US ahead.)

-- Lithography, specifically patterning, is one key aspect, which has garnered significant industrial investment. It is unclear whether advances in optical/ebeam lithography can sustain through 2030. Nanopatterning with superlattices will most probably mature.

-- Probably will never make it in a true sense at the nano scale.

--Developed originally for microsystems, have evolved into critical tools for nanoelectronics.

(g) Discovery/Exploitation of New Materials (with New Properties):

-- There is a shared vision that nanoscience and nanotechnology will dramatically change the performance and function of materials and devices by capitalizing on changes in the structure-property-function of materials when made at the nanometer length scale.

-- Continued improvements in system performance have been enabled by the underlying materials technology, for example, strained silicon and GaN.

-- New IT capabilities, for example, the use of Carbon NanoTubes (CNT) in memory devices has resulted in larger memory systems that are also potentially radiation hardened.

(Assembly??)

(I would disagree as there are no commercial systems available, and hybrid-processed systems are not viable. While research into making CNTs work in a parallel fabrication strategy, one should be critically honest that the possibility of fitting CNTs into high density systems is low.)

-- IBM has developed a product they named Millipede which is a chip containing more than 1,000 heated areas that can make, or read, tiny indentations in a polymer film. (micro not nano)

-- Currently advancement in nanotechnology is a material science endeavor for both properties and fabrication.

-- New, presently unknown, materials could provide a breakthrough technology. Hence, it will be important to investment in new materials discovery and development.
-- Tapping into new materials for new devices is one of the top items in nanotechnology. Consider the benefits of exploring the silicon CMOS transistor over the last several decades. The potential exists for discovery and exploitation of new devices from combinations of materials and material interfaces.
-- Not nano, rather this is chemistry.
-- Materials as an underlying enabling technology for IT appears to be a common theme. An additional important point made is that the ITRS Roadmap has been very influential in guiding the industry.
-- I think the real advances will come from new materials and their new properties coming from working at the nanoscale. The Carbon Nanotubes (CNT) mentioned for memory devices and displays are just 2 examples. I am not sure I agree with the statement that the U.S. is out of the business today relative to CNTs being used in flat panel display technology, given Motorola's advancement in this area. And, Hewlett Packard just announced (1/17/07) a breakthrough that could lead to the creation of field programmable gate arrays (FPGAs) up to eight times denser than those that are currently being produced today, while using less energy for a given computation. They have combined conventional CMOS technology with nanoscale switching devices, using nanowires, in a hybrid circuit to increase effective transistor density, reduce power dissipation, and dramatically improve tolerance to defective devices.

(h) Low Power, Nonvolatile Memory:

-- Present NVRAM has enabled portable, compact, low power IT systems. Advances in this area may well transform the way IT systems are structured.
-- The military will need non-volatile, radiation hard, random access memory. Some examples that employ magnetoresistance technology or MRAM exist today. Nantero has produced prototype devices using carbon nanotubes. The company claims NRAM will be considerably faster and denser than DRAM, have substantially lower power consumption than DRAM or Flash, be as portable as Flash memory, and be highly resistant to environmental forces.

(i) New Displays:

-- New displays are being developed by Motorola that are based on CNT technology—a breakthrough technique that could create large, flat panel displays with superior quality, longer lifetimes and lower costs than those currently available.
-- The CNT is an electron emitter capable of serving as the backplane of a flat-panel display enabling new televisions with no high-voltage components. . . .The US is out of the business today.
-- New Capability: Flexible Electronics – A promising new nanotechnology is based on ultra-thin (<100nm) organic light-emitting diodes incorporated into flexible, bright, and efficient full-color electronic displays. Applications range from head-mounted micro-displays to large flat panel screens that can be rolled up or hung flat on a wall. Printable electronics (based on carbon nanotubes) on polymeric substrates is another example.
-- While display technology is important, I do not believe that it will be as revolutionary in its impact on the way the USAF will affect impact on nation-state adversaries or terrorists. However, this technology development could lead to another technology

miniaturization – nano-enabled vacuum tubes which are radiation tolerant. This would be important for space-based assets.

(j) Plastic Electronics:

-- Although not "nano", plastic electronics for conformable and ultra-cheap electronics is alone very important, and is an important infrastructure for implementing many of the IT-nano capabilities (i.e. as substrates, packaging, and interconnections/communications).

-- I agree with the section on plastic electronics being important advances as they are allowing conformal electronics allowing them to be integrated in systems never before possible, e.g., on the surface of air platforms.

(k) The International Technology Roadmap for Semiconductors (ITRS) Planning Process:

-- Has resulted in the fantastic progress in the past decade as everything got more complex.

-- A world-wide collaboration among the suppliers, developers and manufacturers of all types of semiconductor chips and the equipment to build them to plan out the steps that are needed for the entire industry to stay at or above Moore's Law, however you want to understand that. The entire community analyzes the current state of all of the component technologies (there are now at least 100 different issues being tracked), understands which ones require additional attention, and then plans how to achieve the industry goals. The roadmap comes in both 'near term' (0-6 years) and 'long term' (7-12 years) segments – the near term essentially representing what is in today's development environment and the long term is what the industry is planning on.

-- After collaborating and cooperating on understanding what objectives need to be met by every segment of the industry, the individual companies then compete fiercely to be ahead of everyone else in actually delivering.

-- Near-sighted and IEEE biased.

-- While not a technology advancement, the ITRS has been instrumental in defining the path forward in electronics and has had a tremendous influence in pushing the technology forward.

-- I still think that the most significant issue is that of careful planning as represented by the ITRS, which discusses nearly all of the other items raised by the responders to this question. The major progress has come when a large and involved community has carefully studied all of the above issues and come to consensus on how the industry as a whole can move forward.

(l) Post/Beyond Complementary Metal-Oxide-Semiconductor (CMOS) Technologies:

-- A "must have"

-- Several research activities associated with nanoelectronics that are exploring.

Bio-based nanotechnology is not anywhere sufficiently represented here. It is by far the most versatile and mature technology. It is also a "true" nanotechnology- where each nano-component is uniquely addressable.

(m) Bio-Based Nanotechnology:

-- Not anywhere sufficiently represented here. It is by far the most versatile and mature technology. It is also a "true" nanotechnology- where each nano-component is uniquely addressable.

(n) New Circuit Architectures

(Important Trends)

General Comments:

-- Nature has shaped most of the IT development roadmap in terms of trends of development at the beginning, while performance, cost, and scalability are now driving the roadmap.

(a) Mobile, Agile Modular Information-Gathering Platforms:

(Good)

-- Push toward modular information-gathering platforms containing power, sensors, decision making and communications.

-- The "new" enemy is very mobile and agile, and so the IT that is needed in the hands of the USAF is that which will make the force more mobile and agile. . . . key technologies will enable the people and decision making so that the force can be more responsive.

-- Will be very important – the issue never discussed sufficiently is that power will be a critical issue here. Instead of just making systems with brute force computing (which is high power), there may be low power alternatives.

(b) Increased Information Access Speeds:

-- Need to allow combatants to make timely assessment of situations and act in accordance with policies distributed from command centers.

-- Reaction times will need to decrease, accuracy of decisions will need to increase, and precision of response will need to increase.

(Agree)

(c) Miniaturization of IT Devices (Especially Transistor Dimensions)—Resulting Increased Information Processing and Storage Capabilities:

-- Fundamental limits in precision and size are created by the atomic nature of matter—still a long way away from these limits. If trends continue to this limit we will be able to manufacture complex computational systems in which the fundamental elements are made from some modest number of precisely arranged atoms.

-- IT has been driven by "smaller = faster and cheaper". Periodically, IT devices have been reinvented – always in a way that has enabled further miniaturization.

-- Scaling leads to more transistors per area leading to less expensive chips for given performance and to faster computational speeds. Uncertainty over technical challenges at the nanoscale increases risk with time in achieving the scaling stated in the ITRS.

-- Consensus is that conventional CMOS scaling will end around the 22 to 32 nm node in 5-7 years. Scaling of devices to below 11 nm will require truly exotic nano-devices that depart radically from the CMOS transistor paradigm. However, the accuracy of these technology predictions is suspect due to the departure from conventional scaling.

(The realist. Strongly agree.)

-- Microelectronics as we know it today is a product of nanotechnology. The critical feature size of transistors has been below 100 nm for several years. The critical layer thickness of a transistor has been less than 100 nm for over 10 years. The continued reduction in transistor dimensions is accentuating their nano-scale properties.

-- Nanotechnology is having a profound impact in shaping the semiconductor industry roadmap and future technologies for memory and information storage. Today's logic chips and mass storage technologies already incorporate nanotechnology. The logic chips

in production have 35 nm gates and giant magnetoresistance wire technology revolutionized the hard drive industry.

-- There is still a need for smaller, faster, cheaper computing capabilities which includes processors, displays, memory devices, etc. And, the commercial sector will continue to drive this development as long as that need exists for large volume systems.

-- Sure, systems will be faster, smarter, smaller, cheaper, and have more storage in 2030.

-- Faster and denser storage and CMOS devices are the key to future generate IT technology.

-- There is an insatiable desire toward miniaturization that is extremely important, and most of the input in this section supports that. Included are the trends for cheaper, lighter systems that have more functionality. The military in general is looking for better and faster ways of getting information, faster processing of data, and faster, more accurate communications.

-- The drive to further miniaturization is the strongest trend of those mentioned. It enables greater system complexity at fixed cost and ever smaller form factors at fixed complexity. Over time, it allows the development of entirely new products – cell phones, game machines, global positioning systems, and so on. Finally, smaller components tend to be faster components. However, historical improvements in clock speed are currently stalled because it is becoming so difficult to further miniaturize the silicon field effect transistor. Introduction of new materials and device structures will allow some further progress, but as one of the responders said, "scaling below 11 nm will require truly exotic nano-devices that depart radically from the CMOS transistor paradigm." Straight-line extrapolation of historical trends is not likely to yield accurate predictions in that case.

(d) Far from Known Limits of Fundamental Physics:

-- Even though nearly everything about our devices for measurement, computation and communication will change significantly over the next 25 years, the total rate of improvement in the capability of our information systems will continue to increase at historical rates. This can happen because although we are starting to push the limits of particularly materials and technologies, such as silicon and the field effect transistor, we are no where close to the known limits of fundamental physics for our ability to capture, store, process, transmit and display information.

(The optimist. Strongly disagree. Yes, we are far away from the fundamental size limits, and indeed lab experiments that reach this limit are common today. However, the real issue is power dissipation, due to subthreshold slope, which IS a fundamental limit of charge-based devices. Unless we come up with another switch (possible, but integratable??), scaling WILL end.)

-- I agree that we are far from limits to capture and process information.

-- Gate thickness = 2 atomic layers, how do you divide by 4??

(e) World-Wide Cooperation and Competition:

-- Driver for primary prediction—that at all scales at which we work, our IT devices and systems will have 100,000 times the capability that they have today – e.g. they will keep up with the historical rate of improvement in total capability.

(f) Greater Precision in Manufacturing:

-- Toward greater precision in the manufacturing process, greater flexibility in what is manufactured, and lower manufacturing cost. In the context of computer hardware, these

trends are exemplified by Moore's Law, with exponential increases in memory size, computational power, communications bandwidth and related metrics.

(g) Increasing Amounts of Information to Gather and Analyze:

-- Small, integrated systems enabled by nanotechnologies can help gather information to separate fact from fiction, make accurate decisions, and understand and influence actions and opinions.

(h) Distributed Information Gathering and Decision Making

-- It is not clear how IT systems will be enabled by nanotechnologies in improving information gathering or decision making. Having distributed information gathering and decision-making systems is indisputably a trend, however the role nanotechnology plays in this trend may turn out to be relatively low compared to other technology.

(i) Desire for More Data Storage

(j) Desire for Faster Data Processing

(k) Moore's Law:

-- Trend seems to be holding and there seems to be alternative ways of continuing to achieve the trend even when traditional CMOS technology reaches its end. It certainly seems possible that the trend will continue until 2030.

Topic #2: The emerging trends and limiting factors for nanotechnology in IT development.

(Emerging Development Trends)

General Comments:

-- Nanomedicine will push the development roadmap.

(Nanomedicine a poor word choice, don't need "medicine", rather bio-engineering.)

(Very true, dependant on the definition of "nanomedicine". If this means combining microelectronics with chem./bio systems, then yes. This could also be called "heterogeneous".)

(I seriously doubt the above comment. Computational biology and quantitative medicine will be important for the total demand for IT, but they will not dominate. The big problem here is that these are not wealth creating fields, but rather wealth consuming. We are quickly reaching (or have reached) the level at which we can sustain developments in these areas without going bankrupt as a nation.)

-- The continued introduction of nanotechnology in IT development will be established via niche applications and through the use of novel materials. This will continue until conventional materials/approaches reach their design limits (unless some breakthrough technology occurs).

-- Data transmission and interfaces are a key challenge and opportunity all at the same time.

(a) Heterogeneous IT Integration:

-- Combining various device technologies with a nanoscale interconnect—not yet driven by mainstream commercial interests.

-- Will push the understanding of the physics of how "objects" may be driven and controlled at the nanoscale.

-- Perhaps more of a real revolution in the world around us will come about from the heterogeneous integration of non-computational functions, particularly sensing.

Plastic electronics may be a trend, but even more generally IT integration will be into clothing, the body, and other non-traditional places. Technology from these applications may be more driven by miniaturization, compatibility with the environment, and interconnect reliability.

-- I agree that heterogeneous integration is an emerging trend that will blossom in the next 25 years.

-- The move toward more heterogeneous integration is a positive trend. If progress slows in device miniaturization, resources may be shifted toward integration of heterogeneous functions. Of the emerging trends cited by various respondents, (a), (d), (i), (k), and (l) involve devices and functions that are not currently integrated with logic. These functions are likely to be integrated in the future. Thus, heterogeneous integration appears to be an important emerging trend illuminated by the collected responses.

-- Fundamental changes in circuit architecture and technology integration will be required. This will require the heterogeneous integration of electronic and photonic devices on the same technology platform.

(b) Shift from Top-Down Fabrication to Bottom-Up Assembly:

-- Trends to make smaller integrated systems will continue with a shift toward bottom-up assembly of nanotechnologies, distributed communications, and better algorithms for more efficient data analysis and decision making.

-- I agree that bottom-up assembly (self-assembly) will play an increasing role in manufacturing, and certainly in nanoscale manufacturing. Instead of a replacement of top-down assembly (directed assembly), I think in many applications methodologies will evolve to use both approaches synergistically to simultaneously achieve precision, resolution and deterministic placement.

-- Bio-based one of the best options

-- Strongly disagree. There are no even proof-of-principle bottom-up assembled IT systems. While an attractive concept in theory, it has proven not to give the ability for complex systems. It will have an impact on underlying materials (such as quantum dots) – but instead I would name it correctly, i.e. "chemistry."

-- The use of more "bottom-up" fabrication processes as devices approach the molecular size scale is another positive emerging trend, because such processes have the potential to be relatively inexpensive. So far, however, all the examples are laboratory experiments.

(c) New Metrics:

-- By 2030, IT trends will evolve to be very different from what we see now. The pace of improvement will be measured by metrics other than technology node, as 1 nm and below is the scale for a single atom. Raw processor speed may be de-emphasized while overall computational operations per second will continue to be a metric. Integration density per volume may become a metric as 3D integration improves.

(I agree that new metrics will be forthcoming once we transcend to these new IT devices.)

(I basically agree with the above comment.)

-- I agree with the following comments as ways to think about how to focus efforts on the highest potential emerging technologies, but here is my slant on metrics: information density, information processing throughput.

(d1) Highly Integrated IT Systems:

-- Will include RF, MEMS chemical and biological devices.

(Agree. As we reach the end of scaling, we will broaden out to other applications.)

(d2) Sophisticated "Context-Aware" IT systems:

-- Will be available by 2030 with high levels of sensory perception and internal actuation to physically adapt over time.

(d3) Post/Beyond CMOS Technologies:

-- Very close to the end of the transistor "shrink". Processor clock speeds have already leveled off, although device densities are still increasing. The primary question for leading electronics manufacturers is this: How long can the engineering teams around the world introduce new materials, fabrications processes, and FET device architectures at the furious rate needed to continue the shrink while keeping device performance roughly constant? Once clock speeds start to seriously decline that game will be over. What will be left is the possibility of inventing and developing a new digital switching device for the processing of information. The major US semiconductor manufacturers are already funding university research aimed at that objective under the Nanoelectronics Research Initiative (NRI).

("What will be left . . . (NRI)."—Agree, but we should be prepared if we fail.)

-- Traditional approaches to transistor scaling and integrated circuit manufacturing are rapidly approaching fundamental road blocks to continued improvement. The industry is projecting that a fundamental change will be needed in integrated circuit manufacturing in the 10 to 20 year timeframe. New materials and devices structures resulting from nanotechnology may hold the solution to the way forward. Alternatively, new circuit architectures that can make more effective use of available hardware may enable the continued increase in computational power without radical changes in the underlying transistor structures. Either way, it is clear that the historical approach can not continue. This eminent shift of integrated circuit technology will change the basis of continuous improvement in commercial and military systems.

(I agree with the statement that new materials and device structures resulting from nanotechnology may hold the solution to the way forward.)

-- The planned exploitation of continued advances in microelectronics as practiced by exploiting "Moore's Law" improvement will not continue. New design and architecture constructs must be developed.

-- Silicon Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFET)

-- Ferroelectric Field Effect Transistors

-- Single-Electron Devices for Logic Applications

-- Superconductor Digital Electronics

(I disagree with "superconductor digital electronics" being one of the more important technologies for the USAF. This technology may have limited importance for satellite applications if superconducting transition temperatures can be raised so that cryogenic cooling requirements can be lessened, or it may prove useful for centralized computing and information processing where the cryogenic issues aren't as limiting. However, I do not believe this to be as revolutionary as other emerging technologies could be.)

(I don't think that we will see any real progress in superconducting digital electronics in the next 25 years unless there is a big discovery, e.g. a robust room temperature superconductor. While always possible, I think the probability is low.)

-- Quantum Transport Devices based on Resonant Tunneling

-- CNT for Data Processing

-- Molecular Electronics

-- Going beyond traditional Silicon CMOS technology to alternate architectures. While CMOS will likely continue to be the workhorse of computers for some time, we will start to see faster, smaller computers arising from nanotechnology, whether they be molecular/biological based, quantum based or other. These will likely work in conjunction with CMOS computers initially and applied to very fast computationally challenging problems such as factoring or public key cryptography.

(d4) Quantum Computing:

-- Quantum computers are at present an unknown in terms of their ultimate capabilities and what might be delivered by 2030. Potentially, they could render all widely used public key distribution systems obsolete (although digital signature systems that resist attack by quantum computers are expected to be feasible). NSA is the obvious funding source for further research in quantum computing. What other impact working quantum computers would have is at present uncertain because of the difficulty of developing quantum algorithms for specific tasks.

-- I am not sure what is meant here, but I seriously doubt there will be a true "Quantum Computer" in 25 years. I do think that there will be several applications of Quantum Information, including secure date transmission and possibly new types of radar.

(e) Molecular Computing Using Biological System:

-- Will be challenging, but can be achieved in future.

-- Actually more advanced than the others.

-- I view this as unlikely over the next 25 years. I think that inorganic systems have the capacity to be much faster (e.g. near speed of light, rather than diffusive) and more efficient than biological or chemical systems, and that in 25 years time we will see that clearly.

(f) Assembly Technology at the Nanoscale:

-- May move to play a greater role in integration.

(g) Synergy Between Directed Assembly and Self Assembly:

-- Revolutionary advances can be expected in the next 25 years.

-- A merging of integration technologies will blend new batch-fabrication (i.e. fabrication on wafers) with these assembly techniques to create best-of-class IT systems.

(h) Automatic Configurable and Reconfigurable IT Systems:

-- Will become available by 2030.

(Only viable option is with programmable "bio" based building blocks.)

-- One such vision is to create hardware that can rewire itself on demand at very fine granularity. Such systems may solve relatively near-term technical challenges and, farther in the future, could evolve into computational systems with the ability to learn how to improve their performance with experience and the tools to implement these improvements in situ *(in the original position)* within their hardware.

(An important concept)

-- Another trend is moving away from traditional manufacturing to self-assembly of structures/devices and to new clever approaches, e.g., where the logic gates are developed on a more random basis and assigned post-manufacturing (a variant of this was mentioned in point h) where IT hardware will be able to rewire itself on demand).

(i) Random Access Memories (Various Alternatives Proposed):

-- High-Permittivity for DRAMs

-- Ferroelectric Random Access Memories
-- Magnetoresistive RAM
(Important, but along the ITRS roadmap, and little that nano brings to the table.)

(j) Mass Storage Devices (Various Alternatives Proposed):

-- Magneto Optical Devices
-- Rewritable digital video disks based on Phase Charge Materials (PCM)
-- Holographic Data Storage
-- Analog Front-end Chip for a MEMS (AFM)-based Mass Storage—The Millipede Concept

(k1) Transmission on Chip and Board Level

(k2) Photonic Networks:

-- I think that the future of data communication at all length scales longer than 10 microns is photonic – e.g. near IR or visible photons. This will enable much higher data bandwidth at much lower power dissipation. In 25 years, photonic interconnect will be integrated on chips, on chip modules, and on boards.
-- A place to focus for mid-term applications.

(k3) Microwave Communications System—Novel Approaches for Passive Devices:

-- Microwave will not be a factor because the wavelength is too long.
-- A place to focus for mid-term applications.

(k4) Neuroelectronic Interfacing: Semiconductor Chips with Ion Channels, Nerve Cells, and Brain:

-- Sci Fi - not needed and limited by brain capabilities.
-- A place to focus on for longer term applications (e.g., possibly 25 years away).
-- Highly agree. Plugging into the biochemical system will be a real growth area.
-- Neuroelectronic Interfaces and Smart Prosthetics: An exciting area where breakthroughs are needed. If such breakthroughs occur, IT in 2030 could include cyborg-like interconnect, and other human-IT interfaces that are now only in sci-fi novels. If this comes to be, serious ethical and policy issues will be raised.
-- This will only be a niche application in various types of biosensors – but it will probably be a large niche!

(l) Sensor Arrays and Imaging Systems (Various Alternatives Proposed):

-- Optical 3-D Time-of-Flight Imaging System (Real advance will be in networks of simple systems with advanced output interpretation)
-- Pyroelectric Detector Arrays for IR Imaging
-- Electronic Noses
-- 2-D Tactile Sensors and Tactile Sensor Arrays

(m) Displays (Various Alternatives Proposed):

-- Electronic Paper
-- Liquid Crystal Displays (We are there)
-- Organic Light Emitting Devices
-- Field-Emission and Plasma Displays (We are there)

(n) Improvements in IT Algorithms:

-- A key evolution that should take place in the next 25 years—rather than relying on brute-force improvements in hardware.

-- This kind of revolution is not "nanotechnology". Some algorithmic and architectural developments may be inspired or motivated by nanotechnology material and device developments, however.

(o) Hybrid Insect/Sensor/Electronic Systems:

-- If this comes to be, serious ethical and policy issues will be raised.

(p) Integrated Opto-Electronic Systems:

-- The biggest emerging trend will be their development, and likely even integrated opto-electro-mechano-magneto systems for measurement, communication, processing and display of massive amounts of data in intuitively understandable formats. The biggest challenge will be in terms of power requirements for these systems – we will always struggle to keep the power use of IT systems under control.

(Emerging Limiting Factors)

(a) Statistical Uncertainty in the Placement of Individual Dopant Atoms:

-- One limiting factor in the miniaturization of Field Effect Transistors (FET)

-- Precise placement of dopant atoms would likely be necessary to enable the ultimate miniaturization of such devices.

(b) Power Dissipation:

-- Ultimately limit high performance systems (reference the ITRS).

(Absolutely)

-- There appear to only be three ways around this: i) identify new devices that consume less power (a daunting task, since the physical limits of charged-based devices are fundamental, not technological); ii) identify new architectures; and iii) look for new opportunities for blending electronics with other low power information systems (e.g., biological). The second is the most viable short-term option, while the third is a revolutionary approach for potentially interfacing machines to humans.

-- Base 2 uses the most amount of charge and address space. Move to multigate, say base 1000. Bio uses less power because if uses thermal reversible reactions, but poor for computing unless done the right way.

-- I agree with the following comments as ways to think about how to focus efforts on the highest potential emerging technologies, but here is my slant on power dissipation: focus on mixed electronic and optical information systems (mid-term) and add in the biological/electrochemical for the longer term.

-- Power dissipation is clearly a limiting factor as IT devices continue to get smaller.

-- One of two major emerging limiting factors in microelectronics is growing power dissipation in ever-denser integrated circuits. Of these two limiters, it is power dissipation (or more precisely, economic limits to the amount of power that can be dissipated in a particular application) that is already limiting the further miniaturization of the silicon transistor. Power dissipation is the main reason that microprocessor clock speeds are no longer rapidly increasing, and growing problems with power dissipation are the main reason that respondents put the end of transistor miniaturization at something like the 22 nm technology node. With microelectronics manufacturers striving to introduce a new lithography generation every 2 years, 22 nm generation transistors are only 5 or 6 years away. If no new device is developed to allow further miniaturization of logic circuitry, improvements in integration density and system costs will also slow.

(c) Economics of Manufacturing Process:

-- Because of the existing and extensive semiconductor and mass storage technology infrastructure and our familiarity with Si-based electronics for example, industry will likely stick with current technologies for the foreseeable future. Hence we should expect only incremental changes in ICs, RAM, mass storage devices, and display devices in the near future.
-- To a large extent, the continued growth in computing will be gated by the economics of the manufacturing process. Thus, the ability to inexpensively manufacture the relevant structures will be critical if we are to achieve the goals described above. Existing lithographic methods are unlikely to achieve both the three-dimensional structures and the resolution required for future devices.

(d) Defect Resilience

(e) Interconnect Architecture Reliability

(f) Assembly Methods for Heterogeneous Nanoscale Components

(g) Packaging of Molecular-Level Devices

(h) Heat:

-- The major limitation at this point. There are no fundamental limits to heat dissipation per switching operation provided that the switching operation is logically reversible. Thus, we can reasonable expect switching devices to dissipate less than thermal noise at room temperature. This, however, requires the adoption of computational architectures that are largely logically reversible.

(i) Quantum Computing—Scaling Up to Many Qubits:

-- The limiting factors for quantum/molecular computing are being investigated and vary with the approaches used. Scaling up to many Qubits (a data bit in quantum computing) is a current limiting factor for quantum computing and needs to be overcome.

(j) Scaling Up Molecular Computers:

-- May also be a limiting factor to making workable computers.

(k) Increasing Variability Between Nominally Identical Devices:

-- One of two major emerging limiting factors in microelectronics.

Topic #3: The nanotechnology-enabled IT capabilities anticipated to be at or above TRL-6 by the year 2030.

General Comments:

-- Depends upon the commitment of sufficient investment and resources to the development of a given technology for a specific application.
-- Various nanoscale devices currently being studied by physicists will have matured by 2030 toward engineering prototypes. 24 years is ample time for progress on integrated platforms for a subset of the successful devices. (ITRS map has this happening sooner – 15 years.)
(Doubtful.)
-- While there are many predictions, the most likely major nanotechnology enabled IT capabilities will be smaller & faster computers (which because of their smaller size will become more portable and highly integrated with everything that we do), smaller & higher density storage, and persistent surveillance capability.

-- I have little to add here. I feel all these responses could happen by 2030. The items with perhaps most impact will be distributed “tag” systems, and miniature sensor/comm platforms.
-- Virtually all of these capabilities appear possible and even likely. The most important capability will be enormously greater computational power available at a given cost. The various estimates are simple extrapolations of past and current exponential doubling trends, and should therefore be viewed with some skepticism. Nevertheless, computation and information storage will be much cheaper than it is today under nearly any set of reasonable assumptions.
-- The predictions of computational power and storage capacity will probably happen. I do feel huge strides will come from re-engineering software layers; the big software companies apparently have little incentive to see this happen.
-- Focusing on the end technologies and then providing sufficient resources / investment to stimulate the best ways to make these technologies will drive m, n, and p. A focused investment by the DoD and industry internal research should be made to support creation of manufacturability of nanotechnologies (possibly utilizing m, n, and p), but that is larger than the USAF alone.
-- All of them are important.
-- With the few exceptions noted, I think that all of the above will be available by 2030. Most people were probably being too conservative in their estimates (this is typical – we normally overestimate what can be achieved in 5 years and underestimate what can be achieved in 25 – this is because progress is usually highly nonlinear, and we tend to linearize everything when making extrapolations into the future.
-- This is a crystal ball question. By 2030, it is likely that major advances will have been made in all of the points mentioned. Ten to one thousand times improvements in all forms of IT from processing power to memory to storage will likely reach TRL-6.
-- A coordinated effort at investments among the DOD, DOE, IC, … and industry could help focus efforts and optimize resources to bring these technologies to TRL6 more quickly.
-- By 2030 much of what we do with new computers will be peripheral, minor applications. These functions are what require speed, power, etc., which we will be running into limits for. Further, main functions will be “cognizant” operations, and require less top level speed, power, etc to be useful. Adding 2+2 will be less important and done in the weeds.
-- “Sub-Centimeter Vehicles, “Smart Dust” Systems …Persistent Surveillance Capabilities … used for tags, for information gathering” – an important area. May be the next frontier of security. This could well meld with Electronic-Biological Convergence (i.e., not just for human use, but for autonomous insect/animal surveillance systems.

(a1) Orders-of-Magnitude Better Computing Capabilities—Smaller, Faster Computers (Various Alternatives Proposed):

-- A single processor equivalent will outperform the largest of today’s existing supercomputers on a power budget of a few hundred Watts. In other words, it will have the data handling capacity of 10 human beings. Such systems will make totally autonomous fighter aircraft possible (they will have the equivalent of a crew of 10), but they will be able to maneuver at accelerations that would kill any living thing and make decisions in microseconds. These autonomous systems will be so fast that no human

could fly them remotely—instead they will keep up a running dialog with a human operator, receiving instructions and sending information, but making all tactical ‘decisions’ on board in real time.

(“…of 10 human beings??.” - I can only add 2+2 in the 10 bit/sec range. Already much faster. Typical “IA” miss-representation of the real problem.)

(“A single…decision in microseconds.” - Yes, for high performance systems. But just an ITRS extension.)

-- >1,000X speed increase

(1000X is a bit conservative considering historical trends)

-- Systems able to perform a trillion-trillion logic operations per second (10^24) in a computer smaller than today’s pocket calculators. Manufacturing costs for these systems will be under a dollar.

(The above estimate is not at all credible. This postulates an essentially 17 order of magnitude increase in the performance/cost ratio of computing machines during the next 25 years, for which there is no justification. Moreover, even at the thermodynamic limits of computing, e.g. ~kT per bit operation, a yottaOp (trillion-trillion operations per second) computer would require 4kW of power to operate –forget about putting that in your pocket. Assuming a more realistic but still aggressive increase of 100,000 in performance/cost over the next 25 years, a yottaOp computer would cover about 4 square miles, would cost about $100 billion to build, and would require about 10% of the electrical production of the US to operate.)

-- Nanotechnologies should provide small, fast computers that can be part of multi-functional materials, e.g., they can be embedded in clothing, structures, or other materials thereby reducing size, weight and providing additional capabilities.

(Doubtful, unless substantial proof-of-principle demonstrations can be done in the near term.)

-- *(Either)* Silicon transistors will have matured, and no better substitute for information processing will have been found, in which case, technological advances in devices and circuits will occur at the slow rate found in other mature “systems technologies” such as transportation. IT systems will exploit massive parallelism and extensive use of special-purpose hardware to accelerate common tasks. Hardware may be highly reconfigurable, even at a fine-grained level. Optical communications will be standard for all communications over lengths greater than chip scale, and may be used for on-chip buses as well. There will be a great effort underway to wring performance improvements from drastic simplification of today’s overly layered and grossly inefficient software stacks. In general, innovation will be focused on areas other than the device.

(This is the more likely scenario.)

(Or) One or more “smaller, faster, cheaper” successors to the silicon transistor will have been found and successfully developed for commercial applications, in which case, the cost-performance of IT systems could still be compounding at current exponential rates or higher.

(Computing – I’m betting on the “Or” scenario above with the optical communication interface described in the “either” statement. The next transistors will be strained Si/SiGe or other high mobility device (perhaps GaAs or GaN based) and these will be easily integrated into photonic systems. After we break our reliance solely on Si/SiO2, advances will then be made in other complex material systems that will permit the

continued increase in high density information processing systems – but they may be power hogs. Breakthroughs will be made to reduce the size of high performance computers and increase the capacity computing from distributed networks.)

(I think this is a case of both – I think that all IT devices of the future will be hybrids that have some level of scaled CMOS with photonic and other technologies integrated together to provide something qualitatively different and better than anything that exists today – that is where my 100,000x improvement comes from.)

(I agree with most of the predictions in point a) (in the "either/or" case, I think new alternatives "the or" will occur).)

-- Highly likely that computation power that is limited today to supercomputer class machines that are extremely expensive and require large amounts of power will become common place as a desktop computer is today. This would mean PetaFLOPS (10^{15} floating point operations per second) machines that today require large rooms and kilowatts of power will be available at a desktop. This can be considered a continuation progress of computational power over the past 20 years into ever smaller, lower power packages, but nanotechnology will play an increasing role, not only for the electronics computation engine, but also for interconnects, cooling and packaging.

-- At least one 'supercomputer' that can perform 100 exaFLOPS, or 10^{20} floating point operations per second. This and related machines will be able to create simulation environments for designing and optimizing advanced aircraft with a fidelity rivaled only by actually building the system but with a turn around of hours rather than years.

-- Computer chips with orders-of-magnitude performance improvement over current state of the art will be available. These chips will enable near human like performance from computers as demonstrated by their ability to learn tasks and anticipate situations. These chips will contain electronic, photonic, and potentially mechanical components enabled by nanotechnology.

-- Smaller okay, faster by what definition.

(a2) Totally Autonomous Fighter Aircraft:

-- The autonomous aircraft evolution sounds far out but possible.

(b1) Molecular Computers:

-- Interfaced with our traditional computing systems.

-- Worth research, but unlikely by 2030.

-- While molecular computers will have advanced, it is not clear that these will have reached this level of maturity by 2030.

(b2) Quantum Computers:

-- Interfaced with our traditional computing systems.

-- Early Quantum Information Technology (QuBits).

-- Architectures for scalable and secure quantum communications and computation.

-- Worth research, but unlikely by 2030.

-- Quantum computers will likely reach TRL-6 for a few specialized applications.

-- Quantum computing will be a reality, but for niche applications to solve very difficult cryptographic problems.

(c) Nano-Computers:

-- It is unlikely that the nano-computers will replace existing, advanced technologies by then, but they should be available for specialized applications.

(d) Cognitive Computing:

-- Will be close to being able to do it in real time—although it's full fruition will still be a decade or two away.

(e1) Optical Communications:

-- Extremely high data communications, both over optical fiber and high frequencies wireless technology will proliferate further. Connectivity and access to information will be seemless.

(e2) Optical Information Processing

(f) Smaller, Higher Density Storage (Various Alternatives Proposed):

-- >1,000X density increase

-- Systems able to store a billion-billion (10^18) bits in a cubic centimeter. Manufacturing costs for these systems will be under a dollar.

(At traditional Moore's law rates, storage would be in the range of 1-10 petabits, with a cost of about $100. Thus the above estimate is about a factor of 10,000 above a reasonable upper limit for storage/cost advances. It would likely require another 20 years, or the year 2050, to reach the above projection.)

-- Continued development of advanced memory and storage devices are likely, many showing factors of 10X and greater capabilities.

(This is conservative!)

-- Nanostructures will enable extremely low power, high density memory.

(g) Advanced Displays:

-- Continued development is likely showing factors of 10X and greater capabilities.

(h) Low-Power Nanoelectronics

(i) Non-Volatile Memory

(j) Enabling Technologies for Sub-Centimeter Vehicles:

-- Provide more flexible capabilities to identify and track moving targets in denied areas.

(k) New Materials:

-- Enable power generation, sensors, and secure communications.

(l) "Smart Dust" Systems:

-- At the small end of the scale, we will be able to build systems the size of a particle of dust that will have the capabilities of a laptop of today that will harvest energy from the environment.

(What is so hard about order-of-magnitude analysis.)

-- Able to make some measurements of its surroundings, store data, process some information, and communicate with other dust particles or with a control station. This dust will be small enough to be ingested or inhaled without a person even knowing it. (No no-) It could be used for tags, for information gathering, or for weapons.

-- "Smart dust" is likely to have a major impact because of its ability to provide information about "high value" targets. We should be able to track the location of any human being on the planet. This, coupled with offensive capabilities able to destroy anything that can be successfully targeted is likely to change the fundamental dynamics of warfare. At the present time, one of the major problems that we face is the inability to track individuals who "swim among the people like fish in the sea." This might well change.

-- Never nano! Fundamental limits.

-- Smart dust is not likely to be at TRL6, but investing in smart dust will drive j and many of the other technologies listed in q-gg. m, n, and p could be at TRL 6 but these are ways

that may be used to obtain h-k and q-gg, and m, n, and p are not the end technologies of use.

(m) Molecular Self Assembly (i.e. Chemistry Engineered Toward an Outcome) and Mechanical Self Assembly (e.g. Fluidic Assembly of Micro/Nanoscale Parts):

-- Will have progressed toward application-specific successes to create, integrate and interconnect devices.

(n) Directed Assembly at the Micro/Nano Scale:

-- It is expected that prototypes of assembled systems of heterogeneous nanoscale devices will occur.

-- Direct assembly of specific devices will have been demonstrated.

(o) Configurable and Reconfigurable IT Systems on Chip:

-- Relatively sophisticated prototypes expected.

-- Reconfigurable systems will benefit from advances in resistance change materials, where off/on resistance ratios of at least 10^5 and up to 10^7 are expected.

(p) Parallel Manipulation Systems for Nanoscale Assembly:

-- Lab demonstrations will be a reality.

(q) Electronic-Biological Convergence:

-- A rapidly growing area, presently represented by nano-bio interfaces, such as discrete chem./bio electronic sensors.

-- It is conceivable that a wide range of sensing (and actuating) systems will be demonstrated that spans the range of these interfaces, enabling the ability to “plug into” the electronic and biochemical systems of living systems.

(Okay an interface to bio. Where is the working part that is bio?)

-- Over the next decade, it is possible that we will see numerous sensor systems, with the key accomplishment being able to massively integrate and interface these to IT systems; with the following decade the demonstrations of interfacing to model biosystems.

(Not bio)

-- Not bio if electronic Si. If you use standard electronics to interact with watermelons, does that mean that the system is watermelon based?

-- I am not as certain that the electronic/biologic interface will have reached TRL-6 in this timeframe.

(r) Nanobiosensor Technology

(s) Control and Guidance of Weapon Systems

(t) Ubiquitous Connectivity, Largely Wireless:

-- Will enable both allies and enemies to instantly know what is going on across the globe.

-- Will be enabled by advances in nano-structured materials for antennas and packaging. Advanced transistor structures will also be developed to deliver superior spectral efficiency for wireless communications.

-- Combined with extensive computational power, this will open a vulnerability to computer attack that will dwarf the security breaches occurring today.

(u) Hand-Held Platform Capabilities for Integrating Nano-Enabled Technologies:

-- Can easily integrate different types of small sensor and communication technologies. These platforms should employ faster and more secure technical solutions to improve the automation, integration, analysis and distribution of information to operational forces.

(v) Persistent Surveillance Capabilities:

-- To find, observe, and precisely target enemy capabilities in denied areas is possible.
-- Capability development would be required that pushes the state of the art to smaller scales in power generation and energy storage, sensors for tagging and tracking, new architectures for communication and information processing, and new materials to enable capabilities for the defense and intelligence communities.
-- Will have far reaching and significant impact on the DOD and other agencies when preparing for and fighting the war on terrorism and other asymmetric conflicts.
-- Information gathering / surveillance will be all pervasive around the world's cities and so the DOD will need to learn how to harvest that information. The USAF will need to figure out how to gather the surveillance information outside of cities or where access to surveillance units are not possible (e.g., the enemy owns them and effectively denies access). This is where h-k and q-gg will be utilized. All of these can reach TRL6 by 2030 if sufficient investments are made throughout the DOD, DOE, IC, …

(w) Small, Long-Life Micropower Sources

(x) Remote Creation, Harvesting and Storage of Energy:

-- Refined energy harvesting systems would be an important breakthrough.

(y) Sources and Detectors at Either End of the Electromagnetic Spectrum

(z) New Approaches to Sensors for Chemical and Explosive Threat Detection

(aa) Sensing Platforms for Multiparameter Analysis of Biomolecules and Pathogens

(bb) Higher Efficiency Sensors for Radiation and Nuclear Material Detection

(cc) Single Photon Detectors

(dd) New Imagery Capabilities:

-- To identify and track moving ground targets in denied areas including investments in smaller form factor synthetic aperture radar and related radar capabilities.

(ee) Reduced Form Factor Radar-Responsive Tags

(ff) Anti-Tamper Technologies

(gg) New Methods for Audio Collection and Processing

Topic #4: The biggest challenges to overcome, obstacles to progress, in developing these nanotechnology capabilities for use in IT systems in the year 2030.

General Comments:

-- The two main approaches for building complex structures are (a) self assembly and (b) positional assembly. In self assembly, molecular structures are designed with complimentary shape and charge profiles and so will spontaneously assemble into the desired structure when allowed to move freely in solution. In positional assembly, parts are directly positioned and assembled. Positional assembly at the molecular scale is still a new concept, but seems likely to have great potential for the assembly of molecular devices. Massive parallelism will be needed to efficiently assemble structures with large numbers (billions of billions) of components.
-- The responses show a general level of agreement. Bringing nanotechnology to a sufficiently high TRL for use in IT systems by 2030 requires a staged approach which first involves discovery of new phenomena and then proof of concept for sensors, computing, information processing, … But, soon after the discovery occurs and nearly in parallel with the proof of concept stage, research is needed to identify a technology maturation process for an integrated system to bring it to a level of maturity that would be

useful for the scale at which man can use of it. Then after the integrated system maturation is well on its way, and in parallel, research is needed to identify the manufacturing feasibility. Effective integration of this three stage process across multiple funding resources is the challenge to overcome – coordination of efforts and resources, with exceptional insight to invest in high probability of high impact nanotechnologies.

-- Real challenges arise when we move to quantum and molecular computing, a few of which were noted in points n) and o).

(a) Technology Transfer—From Lab Bench to Field:

-- From lab bench to field—each element of the process is its own stovepipe

-- Bridging the gap from TRL 4 (TRL 1) to TRL 7: identifying which clever ideas have the best chance of being fielded and then putting adequate resources to transition them from clever idea to demonstrated prototypes in relevant environments.

-- The US needs to integrate scientists, engineers, and customers into a more efficient cycle of technology development that brings recognition of new physics, design principles, qualification, and manufacturability all working together at earlier stages in the technology realization process.

-- Right now, scientists don't really understand how they can have an impact that could be fieldable and engineers don't always understand what clever design could be manufacturable. Bringing these groups together to value their respective strengths and identify what technologies could be based around largely unused nanoscale phenomena (i.e. Van der Waals forces, quantum mechanics, etc.) would create a new paradigm in nanotechnology and engineering.

(YES)

-- Requires early, intense collaboration between research and development (R&D) and acquisition management teams; a justified statement of the ultimate users' needs (capabilities gaps); continuous improvement; commitment of the acquisition prime contractor; and, funding for the "Valley of Death."

-- To get low TRL level advances developed in universities and small companies across the "Valley of Death" to higher TRL levels. This may require increased government funding for selected applications.

-- Bringing technologies developed in the laboratories to the market. It took 50 years of work to bring the computer chip technology to this stage. Similar problems will be faced with molecular computing and other IT technologies.

(…with many of the technologies.)

-- Bringing technology from lab to industry for production will be the biggest challenge.

-- Lack of gap funding at all levels, especially from fundamental to trl7

-- A big one.

-- One of the biggest challenges that was mentioned is getting early stage (TRL 1-2) nano-IT creativity into usable systems. The big semiconductor companies such as IBM and Motorola tend to fund and work their proprietary developments with the expressed goals of new products. However, there are a lot of other innovations occurring in university laboratories and small companies where it is much more difficult to bridge the valley of death. Funding is the major obstacle. Another obstacle is getting these groups to work with users of the technologies, e.g., defense contractors for DoD, to make sure key requirements are being met and that there is a market for the technologies. Funding is still an issue here as well.

(b) Manufacturing/Fabrication (Various Opinions Expressed):

-- It is extremely difficult to have a conversation about what manufactured products are possible (as opposed to the structures that have already been built), as almost all researchers are trained to reject feasible structures that cannot be manufactured by today's technology (or perhaps some modest extensions of today's technology). As a warm-up exercise, it is useful to examine some proposals that are clearly beyond today's technology. See, for example, Nanosystems (http://www.e-drexler.com/d/06/00/Nanosystems/toc.html) or some of the proposals by Nanorex (www.nanorex.com and click on "Gallery").

(The above is not credible. It is based on fantasy and really goes beyond what is physically possible, let alone what one can reasonably expect in 25 years. Much of what is contained in the above is rather like saying that the Air Force should put all of its effort into developing faster than light vehicles, ignoring the fact that everything we know about physics states that such vehicles are not possible.)

-- Systematic investigation of a wide range of structures that are inaccessible to today's experimental technologies can be pursued by computational modeling of molecular structures. In other words, we know the laws of physics and we know how to model those laws on a computer. We can use computers to model the behavior of (say) a molecular switch even when we cannot yet build such a molecular switch. At least as important, if not more so, is the ability to model the manufacturing method for making the molecular switch. In essence, we can use massive computational power to let us examine today the manufacturing technologies of 2030—and by so doing can speed the development of these new technologies.

(Unfortunately, today's computers are not up to the task of performing the simulations described above and our fundamental understanding of the underlying physics is not at the level to program such machines if we had them. The types of modeling that could be performed are inadequate to the task of being predictive, especially when any required process would be a non-equilibrium process. There is a lot of fundamental research that needs to be done, and a lot of improvement required. My guess is that the machines available 25 years from now will be just barely adequate to model the manufacturing processes of 25 years from now.)

("we can use massive computational power to let us examine today the manufacturing technologies of 2030" – Doubtful. Do not have an example where it ever helped much.)

-- Our ability to fabricate materials and devices in the lab is relatively easy compared to our ability to manufacture complex, 3-D devices with the precision, reproducibility, and low-cost needed for a viable technology. Today, the necessary standards and reference materials needed to develop these manufacturing principles do not exist.

(I agree.)

-- Handling the complexity in fabricating these systems is a large challenge. Current nanoprocessor efforts for the most part side-skirt this issue of heterogeneity, but this cannot be put off for more than another 5-10 years.

-- The ability to integrate and interconnect heterogeneous devices is a key area for further research. This again raises the issue of manufacturing as the fundamental limit in our ability to exploit new device designs and new (e.g., three dimensional) concepts.

-- If we look at the MOSIS model, that's what got the IC industry going. Perhaps at the right stage (it's debatable when), a similar thing for nano can be done, to spur standardization and application. It would also help funding for the "Valley of Death."
-- Being able to accurately model systems is currently a challenge. With the need to look at systems beyond CMOS, it is imperative that we have good, fast modeling tools that will allow us to do a lot of the design work without entering the lab. The lab should become more of a verification of the modeling. That means a big challenge will be in the manufacturing and scale-up. Can we really have self-assembled logic devices? Can we have logic devices that can be programmed after assembly? These are challenge areas for future nano-IT devices.

(c) Funding for Long-Term, Exploratory Research:

-- The biggest and most obvious challenge to overcome.
-- Don't believe that researchers are currently limited in good ideas. Rather, such long-term research, especially with an engineering systems bent, is resource limited.
-- The critical element is the ability of funding organizations to successfully identify and support the necessary high-payoff, long-term research.
-- All very true. But the big thing that worries me is that present day funding short falls will mean that the supply of American scientists and engineers to develop the technology of the future will be inadequate for the task, and the major developments will occur elsewhere.
-- Most of the above responses were related to the issue of educating a new generation of world leading scientists and engineers. The biggest problem is that funding for exploratory research has collapsed in the US. The DoD, through 6.1 research funding, had a major impact on the educational base of US universities. Cutting back on this type of funding is the equivalent of killing the goose that laid the golden eggs. It is truly foolish, and should be a top priority of anyone who wants to see the US maintain technological superiority. The amounts needed (probably about $10 billion per year now over all research areas, with at least 20% going into nanotech) are a small insurance policy compared to the consequences of ignoring the situation.
-- Funding is a critical issue. There are plenty of ideas – perhaps too many. The problem with today's model is "blue sky" is not funded long-term, if at all (there is to much targeted to short term), and often sub-critically. For nanotech IT to happen, it needs sustained, substantial funding – if even for a few.
-- The biggest challenge to overcome is probably the trend toward greater short-term (<=3 year) research funding driven by deliverables and demonstrations and much less long-term research funding that fuels visions 25 years out. This has been touched upon with several perspectives in the responses. The various detailed technical challenges listed are secondary to the issue above when addressing a strategy for accelerating positive outcomes of research over a 25 year timeframe.

(d) Science and Engineering Training/Education (Various Opinions Expressed):

-- One of the long-term implications of nanotechnology for engineers is that they are going to have to learn quantum mechanics, along with more chemistry.
-- Both graduate and undergraduate education should experience a gradual incorporation of these topics into the engineering disciplines.
-- The next generation of students to develop these nano/IT advancements in the US. I have no doubt that they will be developed, but I worry that they won't be developed first

in the US. Right now, we are effectively killing off our youngest generation of professors in physical science and engineering—there is so little research funding available, that the youngest professors are not able to compete with those who have an established track record. If they don't get funded, they won't get tenure, or they will get discouraged and quit. If the young academic scientists and engineers of today quit, there won't be a next generation of students, since they won't see a future in science and engineering. If we lose our high quality academic research institutions, then it will be up to the Chinese and the Koreans to develop the nano/IT for 2030, and they will.

-- Education is a concern, but it is more a societal problem. Nano has the capability to be a mini-(nano?)-Sputnik, attracting students into science, and we should capitalize on that.

-- Not a technology challenge per se, but I agree that training U.S. workers in nano-IT is crucial. Our current workforce is largely not well trained in most areas of nano including IT. Our universities are populated with foreign students, graduate students and post docs, many of whom will take the nano-IT technologies back to their own countries. We need more education for U.S. citizens across the board.

-- I go back to my original point. If we do not educate a new generation of world leading scientists and engineers, then we will not develop any of the technologies that have been described.

-- Students will follow- technologists follow the money, but need consistency - Defense Advanced Research Projects Agency (DARPA) is killing this.

(e) IT Industry Challenges in Moving Along the Scaling Path:

-- These challenges are: (1) Power and Thermal Management; (2) Parallelism; (3) Complexity Management; (4) Security and Manageability; (5) Variability and Reliable Computing; and, (6) Communication (i.e. Interconnect).

-- Will run into the end of Moore's Law that came from simply continually miniaturizing what we currently do. However, computing power will continue to increase as common personal computers become more and more multiprocessor based. Also, new methods of computing based upon quantum and perhaps biological architectures will begin to be deployed.

-- The most optimistic predictions for computational capability will be correct only if some new device that can be made smaller and faster than the transistor is invented. Since a promising prototype device does not appear to exist at this time, the likelihood and timing of such an invention cannot be judged.

(f) Handling Anticipated Higher Degree of Structural and Functional Variability:

-- In new device technologies that depart from CMOS.

-- Emerging nanoscale devices generally exhibit uncertainty in their behavior and have individual reliability issues. Most envisioned nanoprocessors are expected to utilize nanometer-scale switches with performance limited more by nanoscale interconnect technology than by the active devices.

("Emerging nanoscale…reliability issues." - I do not accept this. Reliability is THE reason for integration. It is more probable to suffer the system-level issues than reliability.)

-- A challenge is laid out to develop new "nanoarchitectures" that are tolerant of defects and faults in the resultant circuits and systems and exhibit overall "black-box" system reliability. This may dictate a departure of the classical stored-program computer architecture that has held steady since the inception of modern computers.

(g) Integration Capabilities:

-- Many present nano demonstrations tend to overlook or underestimate the need to then move to complex, integrated systems. Without integration capability, nano will be relegated to just discrete sensors and the underlying materials infrastructure.

-- New "nanoprocessor" systems are expected to be a heterogeneous mix of best-breed components.

-- Currently, there is considerable research in one-of-a-kind research-grade sensors or computing concepts, but there is little investment in research to solve the science problems arising from trying to create an integrated nanosystem or in research to create better methods of manufacturability for full systems, albeit nanoscale systems. Investments are needed here soon while maintaining a healthy level of research into information processing and data gathering (e.g., sensors, imaging, …) devices / capabilities. A good place to start to address the integration challenges is to formulate a concept vehicle or plan around a platform which requires nanotechnologies for its implementation. This would then lead to a focus on standardization of operating voltages and currents that could be useful without burning out devices or without requiring large power sources. This then leads to the question of how to use nanoscience and nanotechnology to create higher energy density power sources or energy harvesting devices. Integrating all of this into a useable platform that works would then create a focus on the grand challenge of nanotechnology integration in nanosystems.

(h) Various Novel Technical Approaches to Nanoscale Devices and Architectures: (combined w/ (e) IT Industry Challenges in Moving Along the Scaling Path)

-- Include quantum cellular automata (QCA), nanoscale neural networks, nanocells, biologically inspired electronic system structures such as the virus nanoblock (VNB), and hybrid CMOS-nanostructures and self-assembly.

(Nonsense. For supporting data, show me a single commercial system that uses any of these.)

-- The evolving nanodevices are still at the physics investigation stage (much as bipolar and CMOS were in 1960), so most practical engineering and manufacturing issues are yet to be discovered. This progress, and a weeding out of the device technologies can be expected with 20 more years of R&D; this process represents a daunting challenge and an enormous amount of work.

-- Each research camp will no doubt make arguments that their technology is best, but it is too early to make go/no-go decisions.

-- The history of modern electronics can teach lessons here, as competing silicon and GaAs bipolar technology has certain advantages, yet CMOS won convincingly in the 1980's due to the manufacturability and scalability of the integrated system.

(An important lesson. Si is a terrible material, and GaAs is far superior – yet Si won because of manufacturability. Performance is to some degree irrelevant. An analogy – if performance was king, why do we not all drive Formula 1s or Ferraris?)

(i) Implementing Devices and Interconnect at Nanoscale:

-- Current techniques to wire up nanodevices are for the most part not manufacturable.

-- Self-assembly techniques where molecular chemistry plays a role to drive connections through energy minima, is a possible solution. Obtaining heterogeneity with self-assembly may prove extremely difficult.

-- Directed assembly at the nanoscale is worthy of attention, with a goal to continuously improve the ability to deterministically control “objects” at the nanoscale. The challenges in that case are harnessing and controlling various forces (e.g. Van der Waals forces, electrostatic) at the nanoscale, providing rotational degrees-of-freedom for manipulation, achieving nanoscale accuracy and repeatability, and achieving parallel throughput to make such assembly viable from a cost and time perspective.
-- Even after getting parts to where you want them is solved, making electrical contact to nanoscale devices is problematic. Due to the scaling, the contacts exhibit effects on the same order as the active device. Thus, a deep understanding of the entire device plus interconnect system is imperative.

(j) Developing Peripheral Products Needed to Support These Devices:

-- New packaging and heat transfer approaches are needed.
-- Better interconnects, as well as improved communications, are needed to get information to/from the nano-IT systems.
- Needed because the systems will be much smaller by 2030 and will have unique thermal management, packaging and interface problems.
-- I agree that for all very small systems, power generation, thermal management, better interconnects, packaging, and communication with external devices are all still challenges that need to be overcome.

(k) Standard Peer Review, or “Research by Committee,” Process is Broken:

-- Unable to pursue research unless there is consensus in the research community that a particular research objective is both valuable and achievable. By the time every member of a committee thinks an idea is worth pursuing, the research is already out of date. And in today’s competitive environment, serious dissent by one or two committee members is sufficient to block funding.
-- This, of course, assumes that the objective is to pursue long-term, high-payoff goals. Recent funding by, for example, the Defense Advanced Research Projects Agency (DARPA) is aimed at objectives well short of 2030, eliminating even the possibility of pursuing such research. Other funding organizations are also focused on shorter time periods.
(But doing a great job of steering funds that used to go to academia to industry.)
-- This assessment suggests that the primary target of research should be the effectiveness of funding mechanisms. For example, we might modify National Science Foundation (NSF) peer reviewed research to involve review of funded research to see what succeeded, and correlation of the results with the evaluations of individual reviewers. If a reviewer forecast success, and the proposal subsequently produced successful results, the reviewer’s opinion could be given greater weight in the next round of proposals. Financial or other incentives to individual reviewers based on some measure of success of the proposal would also be an area to pursue.
-- Market based forecasting and feedback schemes have been discussed for some time now, see for example: http://en.wikipedia.org/wiki/Prediction_market. Application of these ideas to research funding should be effective in improving the quality of funding for research—and the quality of the funding process is critical.
-- Systematic research on how to improve the effectiveness of research needs support sufficient to overcome opposition by those who benefit from the current state of affairs and who might as a consequence slow or block change. This is a real concern, as the

author is personally aware of a research proposal to NSF aimed specifically at increasing the effectiveness of the peer review process that was withdrawn (rather than evaluated and rejected) following pressure on the submitter. Changing how research is funded can adversely affect existing beneficiaries of the system.

-- I agree that key issues are how the research to be funded is chosen. This funding has to be done in an environment that fosters education and career growth to replenish the next generation of technical leaders.

-- The fact this comes up says the scientific community is unhappy with the structure, and do not that it is intelligent or fair. This cries out for a more distributed model of funding – some very consensus, some very "blue sky". This theme occurs repeatedly – the inability to fund "blue sky".

(l) Improving the Quality of the Funding Mechanisms (combined w/ (c) Funding for Long-Term, Exploratory Research)

(m) Preconceptions:

-- The biggest technical challenge is envisioning the goal without limiting ourselves by our biases about what is possible. Computers are made from atoms, and our ability to make better computers depends ultimately on our ability to arrange atoms in precise and complex patterns. Thus, in forecasting future developments of nanotechnology for computers we must first ask what arrangements of atoms are possible and useful (without limiting ourselves to present-day manufacturing capabilities) and then ask what sort of manufacturing system would be able to produce the desired result.

-- The approach to computational chemistry and computer modeling is in contrast to today's approach, where computational methods are used to model structures that have either already been built or might soon be built. We need to deliberately abandon the limitations of today's technology, and consider what the basic laws of physics permit. Such an examination, backed up by rigorous computational analysis, can provide us with insight into the new capabilities that could be available in a few decades time.

("…We need to deliberately abandon…into the new capabilities …" - Nonsense. The lesson of microelectronics is that it doesn't matter what is best or permitted, it is what is cheap.)

-- Lowest bidder version of R&D is: The biggest claim up front. We need to stop rewarding industry for evolutionary improvements and academia for huge claims.

(n) Getting Stable Molecular Computers to Work:

-- Need those that are chemically stable for long periods of time and that are environmentally stable at various temperature/pressure/other environments.

-- A laudable objective, but is already far behind for 2030. We should continue to fund research in these, but at a very low level, and understand that these are 50+ yrs off, if at all. Much more realistic are other far out ideas, such as bioelectronic interfaces.

(o) Getting Quantum Confinement Schemes to Work Reliably for Quantum Computers:

-- A laudable objective, but is already far behind for 2030. We should continue to fund research in these, but at a very low level, and understand that these are 50+ yrs off, if at all. Much more realistic are other far out ideas, such as bioelectronic interfaces.

(p) Memory Devices:

-- Right now, there are many new non-silicon approaches under serious commercial development. Phase change memory (PCM) should be introduced to the market shortly.

Magnetic random access memory (MRAM) is available from Freescale. Both devices appear shrinkable to 10 nm dimensions.

-- The obstacles are those that face any new product on the market. These new memories must compete in the marketplace with the established silicon memory devices. PCM is expected to eventually win in the non-volatile (Flash) memory market (cell phone, cameras, etc.) because the further miniaturization of silicon, non-volatile memory is believed to be very limited.

-- The forecasts regarding memory and mass storage devices are basically a "done deal", since new non-volatile memory devices (such as phase change memory) are already entering the market, and these devices do not suffer from the same limitations to scaling as field effect transistors. Consumer electronics will provide the economic driver for these developments.

(q) Control and Reproducibility of Nano-Scale Structures: (combined w/ (b) Manufacturing/ Fabrication)

-- New manufacturing techniques will be needed to deliver sub-10 nm structures.

-- Bio!!!

(r) Power Generation and Storage:

-- Fundamental challenge to realizing ubiquitous computing and connectivity. As a nation we are becoming critically dependent on foreign sources of energy. If we do not have sufficient power, others can catch or exceed our nation's capabilities in all areas.

-- Limited possibilities

-- POWER! The single largest problem for realizing the full potential for nanotechnology enabled IT capability is the ability to dissipate waste heat and the ability to supply the required power. Today one of the fundamental performance limitation of integrated circuits is the power dissipation due to none ideal switching (active and standby power loss). This power dissipation limit the speed of operation. Nanotechnology enabled devices are promising to reduce the power budget.

-- Even if/when the power dissipation problem is solved (or more accurately moved to higher levels as there will always be an upper bound), there will be limitation on the available power as embodied by power generation, storage, and delivery. This is the single largest barrier to realizing the full potential of nanotechnology for IT in 2030.

(s) Thermal Issues:

-- The new technologies, and the continual miniaturization of what we have now, will continue to have increasing thermal issues that will need to be addressed.

(t) Big Industry Usually Very Conservative

-- Even though nanotechnology will likely develop new concepts and materials that could lead to improved or new capabilities, these concepts and materials may never be developed as big industry is usually very conservative. For any new technology to be successful (in addition to taking 10 to 20 years to develop) it must be readily manufacturable, affordable, scalable, and competitive in a perceived market.

(u) Development of Highly Capable Sensors:

-- The development of smart dust and the various highly capable sensors mentioned by respondents is not generally driven by the economics of any existing products. The emergence of such devices and systems will depend on funding of research and development motivated by potential new applications.

(v) Interagency Coordination

Topic #5: The impacts nanotechnology in the realm of IT will have on the world in 2030.

General Comments:

-- The devices of digital information technology are: Logic (switches), Memory, Interconnections (wires, waveguides) Transducers (sensors and other input and output devices), and Energy Supply (batteries). Nanotechnology will improve all of the attributes of all of these devices. All will be available in the consumer marketplace built into a wide variety of consumer products.

-- The world today has been transformed by IT in many ways over the past 25 years—think of how much more powerful computers are and all of the new things that exist today—a cell phone that is a camera that is a personal digital assistant. The types of changes that have occurred in the past 25 years will occur in the next 25 years. In general, the world will be both much more efficient and it will be much more difficult to keep a secret.

-- All of these responses appear possible and even likely. Since the cost of information processing, storage, and communications will continue to plummet, nearly every manufactured object will have some "intelligence" and some ability to network with other devices. It will be trivial to give nearly every product a tag which contains data about its manufacture and subsequent use, and which can be interrogated by an appropriate reader. It will be trivial to give nearly every object (for example, a light bulb) an internet address. History tells us that it is very difficult to predict how such raw capabilities will be used. In a world like that, we will leave traces of our comings and goings in every interaction we have with people and with things. The "reconnaissance fly" may not be much needed.

-- I think of these as IT-focused nanotechnologies, rather than IT-based. Again, nanotechnology will become easy to embed in many other applications, thus changing the overall functionality.

-- I agree with all these assessments. It does strike me as amusing that all of these diverse research areas are brought up under the guise nanotechnology! What is often being discussed is the impact of IT, not necessarily nanotechnology on IT. I think this is fine, but underscores that investments should not hinge on labeling something nanotechnology.

-- The answer to this question follows from earlier answers. Communications and data processing will revolutionize how we interact with each other and our environment. This will change how confrontations occur (e.g. in cyber space, on the network, etc) and introduce new vulnerabilities as well as new capabilities.

-- There will also clearly be major advances in individual technologies brought about by nano-IT, many of which were mentioned: vastly improved encryption/decryption (we are already seeing this in advancements in Quantum Key Distribution); vastly improved weapons that are more readily available than today, more intelligent systems; smaller, more sensitive sensors; improved communications, etc.

-- There were many comments on essentially linear extrapolations of present technology – the new ideas that struck me were: (1.) Small, Cheap Sensors - an artificial fly; (2.) the interfacing of biosensor systems.

(a) Improved Connectedness—Better and Faster Communications:
-- Everyone will be 'connected' via commercially available products. Our way of life will be highly dependent on portable electronics and IT. Militarily, nanotechnology and IT will create smart networks, provide instantaneous information (and knowledge), persistent surveillance and situation awareness, etc.
-- We will be able to access the internet at much greater speeds than we do today. Information of all kinds will be at our fingertips. More tasks will be done on-line, e.g., more banking, buying/selling, etc.
-- Communications bandwidths will be much higher.
-- Improved (better and faster) communications and connectivity by far. The comms and connectivity will become integrated with a variety of sensors (a parallel development also being enabled/enhanced by nanotechnology). These developments will lead to significantly better persistent surveillance and situation awareness.
(b) Vastly Cheaper Memory:
-- Need reliability of system and simple interfaces, then it will take off.
(c) Much Faster and More Power-Efficient Processors
(d) Small, Cheap Sensors:
-- Think of an artificial fly that can record audio and video and then transmit that information in a secure manner to a host.
-- Can be widely distributed in the environment to gather, analysis and distribution information.
-- The theme of small cheap sensors will have a major impact on future Air Force operations. The ability to monitor even the most hidden of opponents and the most stealthy of weapons will have a major impact.
(e) Intelligent Weapons Systems:
-- As computational power increases and size decreases, we will add intelligence to almost everything. Obvious military applications are smart weapons – smart bullets with the power of today's super computers, for example. The terse answer "better computers" does not do justice to the possibilities.
(f) Improved Encryption/Decryption Capabilities
(g) Improvement of Materials:
-- Such as quantum dots for low power lasers, and membranes for fuel cells.
(h) Electronic-Bio Sensors and Systems:
-- Have the potential for tremendous impact if integration complexity (with fidelity) can be achieved.
-- Applications include the interfacing of biosensor systems to electronics (human for obvious applications; animal and insect for distributed sensor systems), security (DNA and biochemical identification), and potentially enabling blue-sky biomolecular computing.
(This is blue sky, while the rest of this manuscript isn't????)
(i) More Information Readily Available to Almost Everyone Worldwide:
-- For example, our medical information whenever and wherever we need it.
-- Each of us will have an overwhelming amount of information available to us, and most of those advancements will be because of nanotechnology.
(j) New Business Models:

-- With faster information flow, IT-based nanotechnology will enable more people to work remotely and thereby affect business's financial situations.

-- IT-based nanotechnology will make it easier to do product development from multiple companies, multiple places anywhere in the world (i.e., the world will be getting flatter). This could affect global trade and our relationships with other countries.

-- Will create new capabilities that also will permit the development of new business models and new capabilities by small groups of individuals (Will people be able to create sophisticated individualized medical devices, for example?).

-- I tend to agree with all of the inputs in this section. However, I see the major impacts to be in the new business models because that is where we can expect global changes, for example: in the way we work, how and where we get our next generation technologies, and how we interact with other countries (both friendly and not). And, who will be the technology powerhouse in 2030, the leader of information dominance and defense capabilities?

(k) New Security Threats:

-- Individuals may be able to create the equivalent of hardware viruses and worms that bring down large scale systems.

(l) Unimagined, Revolutionary Applications:

-- If the miniaturization of IT devices continues with the invention of new devices to replace the transistor for information processing and memory, then the cost-performance of IT systems will still be improving at current rates or greater. Historically, the important applications of ever-cheaper IT have always surprised us. I cannot imagine the important new applications of IT in 2030 if cost-performance is, say, 100,000 times better than it is today.

-- New physics, design principles, qualification, and manufacturability all working together at earlier stages in the technology realization process. Bringing scientists and engineers together to value their respective strengths and identify what technologies could be based around largely unused nanoscale phenomena (Van der Waals forces, quantum mechanics, etc.) would create a new paradigm in nanotechnology and engineering.

(m) "Software-esk" Development Cycle:

-- The development of nanotechnology will in some sense follow a parallel path to that we saw in IT capabilities in software only this time in hardware. It took an enormous investment of time, people and money to develop the software infrastructure we have today. Once developed however, this infrastructure allowed individuals to perform tasks of tremendous impact (positive or negative) that once could only be developed by teams of individuals. For example, a small number of people could write software that enabled completely new business models (e-Bay, Amazon, etc.) and that relied on the IT infrastructure already in place. At the same time individuals could also write viruses and worms that could do tremendous damage to that same infrastructure.

-- Speaking of S/W. Imagine "Vista" running a system 100,000 times more complex. Can you say blue screen of death 100,000 times faster? S/W is critical.

(n) Human Health

(o) Control Over Weapon Systems

(p) High Storage Systems—Faster, Cheaper, Lighter

(q) Much More Efficient and Effective Technologies:

-- All of our IT and related technologies will be orders of magnitude more capable than they are today, which will translate into much more efficient and effective technologies of all types.

(r) Faster Product Development Cycles—Especially Military Platforms:

-- All of our IT and related technologies will be orders of magnitude more capable than they are today, which will translate into ever faster development cycles for all types of products, including and especially military platforms.

(s) Significant Qualitative Paradigm Shifts:

-- Probably the most important developments will be ones we can't even anticipate now, since large quantitative technology improvements always lead to significant qualitative paradigm shifts. In 1980, who could predict that China would have over 250 million cell phone users today?

(t) Ubiquitous, Networked Information Gathering:

-- There will be information gathering everywhere, all the time, for good, or bad uses.

-- Distributed, networked information gathering will be enabled to permit better medical treatment options, better banking and trade options, and hopefully better intelligence for better policy options.

-- I can see the world getting overwhelmed with information which could lead to worse policy decisions or if exceptional information processing algorithms and hardware are created, then better policy decisions could be the outcome.

-- For the USAF, this scenario of pervasive information gathering and dissemination would also translate to better options for evaluating tactical and strategic actions.

Topic #6: The potential, "technology surprises" anticipated with IT-based nanotechnology in 2030 resulting from the forces of globalization and commercialization.

General Comments:

-- We won't own all the clever nanotechnology ideas, and moreover we won't bring most of them to market.

(I agree)

-- "Technology surprises" are not likely to *directly* undermine US military preeminence. Presumably the US will continue to be a leader in the use of new technologies for military purposes. However, I think that ever cheaper and more pervasive IT (which includes communications technology) will make it ever more difficult to determine who the enemy is and where the enemy is. That seems to be the current path for international terrorism.

(I disagree with the following remark: **--** "Technology surprises" are not likely to *directly* undermine US military preeminence. Presumably the US will continue to be a leader in the use of new technologies for military purposes." I believe that nanotechnology will create a new paradigm in military attacks and targets. Therefore, we would be at risk to attack on our communication and information-based infrastructure from nanotechnologies that we are unaware could exist. The good news is that these nanotechnologies first appear as discovery concepts in the scientific community and then turn into technological uses. As long as the US remains engaged with the international

nanoscience community, then the element of technological surprise from a nation state should be minimized.)
(The above comment presupposes that we maintain our educational system and train the next generation of scientists and engineers in the US. Unfortunately, given the present trends that I see, this will NOT be the case unless some fairly dramatic action is taken.)
(I disagree with the statements that "Technology surprises are not likely to *directly* undermine US military preeminence, and presumably the US will continue to be a leader in the use of new technologies for military purposes." We are already seeing very significant advances in technology (IT, nano, others) outside the U.S., especially in China, Taiwan, India, and others. To think that the U.S. will presumably continue to be a leader over the next 23 years is extremely dangerous. The U.S. is barely keeping up in the nano investments with China and other countries ramping up much faster than we are currently.)
-- The US has broad-based research funding in all the critical areas, although many researchers are constrained by application focus. "Surprises" will occur from unanticipated exploratory areas, and the decreasing amount of curiosity-driven research in the US has a deleterious effect on being competitive in these areas.
(And, do we really have broad based research funding in all critical areas? That statement, too, seems dangerous.)
(I see problems with the following remark: -- "The US has broad-based research funding in all the critical areas, although many researchers are constrained by application focus. " This statement and its follow-on sentence imply that most research is focused on applications and that this is bad. As I wrote above, it is important to remain engaged with the international nanoscience community to avoid technological surprise from new discoveries, but it is also important for us to keep an eye to how to transition our own new discoveries to mature technologies (where highest priority impact is expected) more easily and quickly. We do not do this as well as we should in the US and so we may be at equal risk to technology surprise from loss of connectivity to fieldable technologies as we are to surprise from new discoveries in science.)
-- We need to move faster by out-spending and supporting our researchers and suppliers and having a more nimble system. Close the purchase side, not the IP side.
-- The continuing advances in communications, computation, and sensing could work to the benefit of the U.S. The ability to conceal individual behavior when we have distributed sensors able to monitor every person on the planet, and computational ability to do speech and vision recognition on the data stream so generated will let us rapidly identify and respond to threats. The current advantage provided to asymmetric attackers might be reversed.

(a) Implications of Overseas Microelectronics Outsourcing:

-- An area of concern which potentially has impact on security by "unreliable chips" (i.e., hidden Trojans), and potential superiority in NVRAM.
("unreliable chips" (i.e., hidden Trojans) – very true, although this should be a mandate of NSA or DHS.)
-- Corruption of our sources of microelectronics could bring the US unforeseen problems. Historically the US military has relied on captive, or at least on-shore, integrated circuit (IC) foundries. Growing capital costs and changes in market demographics is shifting a large fraction of the IC business off-shore. In addition, the traditional US Defense

contractors can not afford to maintain low-volume foundries to supply chips to the Department of Defense (DoD). Both of these trends put the trustworthiness of microchip fabrication outside of government control, at risk. If the microchips in defense systems are compromised, the foundation of our national defense is at risk.

-- I agree that outsourcing of more and more of our IT components is a potential risk. The U.S. defense should have trusted foundry capabilities in the U.S.

-- Globalization means that some critical materials and some critical parts for systems will have to be sourced outside of the United States. Some of the best experts in key areas of technology will not live in the United States. Economic forces generated by free markets and free trade drive things in this direction. The US government can limit this exposure by subsidizing US developers and suppliers in the name of national security. This has always been done to some extent, but truly massive subsidies would be required to protect our position in IT. That is because IT becomes more ubiquitous every year. Ubiquity implies large volume manufacturing for global mass markets. The very highest-performance computers will be built from parts made for game machines (or something even cheaper and more familiar). In general, the benefits of information technology will be available to all – enemies and friends alike. I see no developments that will reverse these trends.

-- As we become more dependent on microchips for all our communications, system control, data analysis, etc we also become extremely vulnerable to compromised components and software. The opportunities for malicious threats increases as both hardware and software development and production move off shore.

-- Nanotechnology will be ubiquitous; our foes will be more capable (particularly in cyberspace). I see a doom and gloom forecast when coupled with our continued outsourcing of technology. We will become dependent on more than just foreign oil.

(b) Another Country(ies) Overtakes US as Technology Lead:

-- Within this timeframe it is expected that nations in the Pacific region will become (if they are not already) the preeminent manufactures in the world and in fact the US will be buying most of its IT technology from there. And so it follows from this that indeed the US military may no longer be the predominant IT–based force in the world.

-- If other countries become more innovative than we are and are first to invent the new nano/IT. The primary country that I think of in this respect is China. I was in a meeting in Japan a few years ago, and one of the Chinese representatives at that meeting boasted that there were 30,000 young Chinese studying nanotechnology related subjects (I would guess that the number in the US is more like 3,000). This may have been an exaggeration, but any international conference I attend now seems to have as many Chinese attending as Americans and Europeans. I see more and more papers from China in the journals, and they are getting better in quality. The Chinese are benchmarking our educational system, and they are slowly but surely making improvements and catching up.

-- Waking up after a couple of decades of complacency and neglect of our research infrastructure and finding out that we are being outclassed.

-- I totally agree with the statements about China becoming a nano-IT superpower. It would be dangerous if the U.S. did end up buying most of its IT from them.

-- I still say the biggest technological surprise would be that we have become second rate and there are many adversaries that are better than we are. The best way to avoid technological surprise is to have the best technologists.

-- The potential for foreign countries to overtake the U.S. in innovation, whether in nanotechnology, IT, or other areas.

(c) Self-Replicating Weapons Systems:

-- Biggest potential "technology surprise" that might undermine US power. For a recent review of self replicating systems, see http://www.molecularassembler.com/KSRM.htm. Various scenarios involving artificial self replicating systems are reviewed in http://www.foresight.org/nano/Ecophagy.html (generally referred to as "gray goo" scenarios).

-- Existing biological replicating systems demonstrate feasibility. Artificial replicating systems with enhanced capabilities seem entirely feasible. Research in this area is grossly underfunded when considered in the context of either its remarkable economic value or the potential risks. Note that when evaluating risks, a small probability of successful implementation of a novel WMD poses an unacceptable risk to national security.

-- The above is pure pseudoscience. I would put the probability of such an advance in the next 25 years as being less than one in a million. There are no credible demonstrations of the types of self-replicating systems envisioned. A far more credible threat, which has a probability of essentially 100%, is the weaponization of some highly contagious viral infection. When weighted with reasonable probabilities, such fanciful predictions as the above are of no concern.

-- We already have them, they are called viruses. Anything we can artificially make is far outclassed by what nature does very well.

-- The discussion of self-replicating weapons systems is a red herring. The reason research on self-replicating nanotechnology is "grossly underfunded" is because its proponents have not defined the simple and basic experimental steps that are critical to advancing their long-term goals. That strongly suggests that the vision is more than 25 years away from realization. But let us suppose that such systems appear much sooner. In a connected, globalized economy, it is beyond belief that the required string of fundamental advances in physics, chemistry, etc. (each discovery with its own set of potential new applications to be immediately realized), would occur in such isolation that any one country would end with a significant lead in self-replicating nanotechnology. The (military or economic) competitive advantage would not reside in the ability to produce self-replicating systems, but rather in the ability to design such systems to do useful things. For a reasonably balanced view of prospects for "molecular manufacturing", see the recently released National Research Council report, *A Matter of Size, Triennial Review of the National Nanotechnology Initiative.*

-- Biological WMDs, self-replicating or not, may prove to be a serious threat by 2030. These may or may not be nano-enabled.

(d) Controlled, Light-Weight, More Powerful Warheads:

-- May pose danger to US military if they are in wrong hand or developed by other countries.

-- Obvious.

(e) Communications and Computing Technology Based on Quantum Information Science Maturation:

-- This field exploits physical quantum effects at the atomic scale that theorists predict can lead to many orders of magnitude improvements in specialized computing and extremely secure encrypted communications. The threat relates to the ability to rapidly perform specialized data searches over a million times faster than is possible today. This could compromise some militarily critical capabilities.

-- Crypto we can't crack.

-- The US dependence on robust cryptography for military communications could be undermined if significant progress is made in quantum information science and technology.

-- A NIOL (not in our lifetime) technology. Although an interesting research area, the technological barriers are SO huge, and the run-arounds (i.e., don't use prime number factoring) so easy, that this is doubtful.

(f) Information Gathering and Decryption Breakthroughs:

-- The amount and complexity of information gathering against us could increase considerably as a result of nanotechnologies being developed and produced world wide. Distributed, autonomous units could collect information and distribute that information at infrequent intervals such that there is a low probability of detecting or defeating the unit.

(g) Portable Computer Attack Capabilities:

-- Could be used to attack US networks and infrastructure.

(h) Harvesting and Production of Both Energy and Water:

-- The US may focus solely on what it takes to produce large amounts of energy for a large force while adversaries may control the ability to create and/or harvest small amounts of energy at point of use for distributed units (units may be man or machine).

(i) New, Small-Group Business Models and Capabilities

(j) "New-Wave" Attack Capabilities—e.g. Cyber Attack, Hardware Viruses and Worms:

-- Our whole IT infrastructure may at some point be in jeopardy. As an example, our military systems may be subject to cyber attack. An instantiation of this would be our information coming from satellites being disrupted. Or, our power systems could be immobilized. We could become much more vulnerable than we are today.

-- Capable of bringing down large-scale systems.

-- I am not an expert on this, but this is what worries me most, although there is no "nano" here.

-- Computer virus and worm based attacks could indeed cause major problems to existing and future weapons systems. As electronic control becomes pervasive the ability to corrupt that control will be an increasing risk factor.

-- So are we (the Air Force) to use MicroSoft for everything??

-- More stealthy attacks on our information systems. Just as we will want to utilize distributed information gathering and processing systems, our adversaries will want to use these against us and may deploy inherently stealth capabilities that form a distributed network which can attack our information networks, our energy grid, distribution networks, …

(k) Exploitation of IT-Dependent US' Security Holes:

-- Exploitation of security holes in a nation increasingly dependent on IT in all aspects of life.

(l) Environmental Challenges

(m) Nano-Enhanced Weapon Systems:

-- Those with nano-powders such as Al, may result in our adversaries having much more powerful weapons at their disposal than they currently have, and in large numbers and fairly cheaply.

(n) Radar Jamming

Topic #7: The threats envisioned to come from terrorists combining nano- and information technologies in new and dangerous ways that will impact the USAF mission in 2030 and beyond.

General Comments:

-- Nanotechnologies can be developed or used by relatively low technology groups or countries, giving some of our adversaries' access to more modern technology than they have had in the past. This fact can change the military playing field dramatically.

(Yes.)

-- The battle is on—they will try to use nano- and information technology to understand our societal and military vulnerabilities better (and faster) than we do, while we are trying to do the same in understanding their vulnerabilities. The key difference is that we are a visible target and they are not fully visible. Therefore, we have greater need to also create information tagging and tracking technologies (both nano and non-nano) which can identify who is the adversary, with precision and proof in the identification process.

(Yes.)

(I agree.)

-- Although there are significant threats from nano (e.g., toxic nanoparticles) and from IT (e.g., information security), IT-nano requires massive, visible investment, so threats seem minimal.

(No.)

(Disagree.)

(I do not agree with the above comment at all. I think that there will be very cheap commercial technology available in 25 years that can be easily and stealthily 'weaponized' – think about thousands of programmable toy cars or planes that are modified to deliver explosives or pathogens used to overwhelm the defenses of a critical facility.)

(True, if "IT-nano" is defined as making next generation IT systems from (as yet undefined) nanodevices – i.e., this is the IC industry. This is very visible.)

(I do not agree that IT-nano necessarily requires massive, visible investment therefore the threat would be minimal.)

-- I do not see a "new and dangerous way" in which terrorists will combine nano- and information technologies.

(Yes.)

(Disagree. Our ignorance in understanding how terrorists will think to use nanotechnologies against us simply reflects our ignorance, not their ability to harness support for development and use of weaponized nanotechnologies.)

(See above comment: “I do not agree…overwhelm the defenses of a critical facility.”)
-- A lot of nanotechnology work is done using beaker chemistry and does not require many resources. Combination of nanotechnology and IT may be dangerous.
(No)
(This does not follow. True, chemistry (call it nano if you wish) can make some nasties, but how does this combine with IT? I don’t see any path.)
-- I think that the statements that the combination of nano and IT do not pose a significant threat from terrorists are very naïve ones and ones I do not agree with. The terrorists have already demonstrated that they can successfully use the internet and IT technologies to their advantage.
-- I do not see terrorist organizations as well suited to mounting complex attacks on system software or hardware as described in the answer to question 6. Hardware attacks, and probably complex software attacks on Defense systems, are more likely to come from well coordinated and financed nation states (e.g. China).
-- Terrorist adversaries have shown that they are educated, in tune with and use modern technology, and focus on how to use simple existing capabilities that we have in the open “market” to attack us with our own technological developments – whether they are airplanes or cell phones. Therefore, I would expect this trend to continue and that open market developments in nanotechnology will then be used against us in the future. However, many of these nanotechnologies may not be those invented, developed, or manufactured in the US and so we may have less control over what gets into the open market and if we are not integrally in the invention-development-manufacturing loop, then we may not have the technical expertise to fully judge the potential uses of these types of technologies.
-- I believe the nature of the world will be far different in 2030 due to the diminishing global oil supply and because resulting economic hardships will create a world where cultures routinely clash. Terrorism may not be the biggest issue by 2030, but rather conflicts between nations, assuming we don’t have a major world war before that time.

(a) Cyber Attacks on US IT Systems and Critical (Computer-Controlled) Infrastructures:

-- Cyber-terrorism threatens to undermine the internet for commerce and military applications. As the US becomes ever more dependent on internet connectivity this vulnerability could be exploited.
(Yes.)
-- Increased cyber attacks are most likely especially since our aging infrastructure will be very vulnerable.
-- Absolutely. But there’s no real “nano” here.
-- Cyber warfare is well suited to small groups of highly specialized experts. This fits very well with current and future terrorist organizations.
-- As our use of IT increases from applications of nanotech, there will be more opportunities for information interception and Cyber terrorism.

(b) Infiltration of US Command, Control, Communications, Computers, and Intelligence (C4I) Networks:

-- Because we (the Air Force) choose Microsoft

(c) Encryption Capabilities:

-- Able to thwart US surveillance and information-gathering approaches making America's defenses less effective and also making it harder for the US to track terrorist actions.

-- Because we (the Air Force) choose Microsoft

(d) Sophisticated Jamming and Counter-Surveillance Technologies

(e) Improved Intelligence-Gathering Capabilities:

-- More IT capabilities bring with them increased security risks on our end. Terrorists may have more opportunities to gather intelligence information on the US armed forces giving them a better advantage than they have today.

-- Ability to track our forces taking away some of our military advantage.

-- The biggest threat from terrorists' use of advanced IT in 2030 may be in advanced surveillance and deployment of activities. The actual weapons used may be an issue but there are already plenty of choices, many of which are low cost.

(f) Intelligent Reasoning Devices:

-- Will be coming online, and will be available to all.

-- Doubtful. As was once said, "it's called *artificial* intelligence for a reason."

(g) Self-Replicating Weapons Systems—Biological or Artificial:

-- Could be manufactured in small facilities (particularly when compared with the large facilities required for nuclear weapons), would be easy to disperse, and difficult to monitor.

-- Self-replicating systems (other than the biological ones we deal with every day) will not appear by 2030.

-- Again, the self-replicating part is pure fantasy. However, it would be very easy to take inexpensive commercial things like toys and modify them to be weapons. This is a far more likely scenario than the above.

-- I'm less fearful of self-replicating weapons by 2030 than I am about the use of weaponized biological and chemical nanotechnologies for weapons of fear.

-- Called anthrax- already dealt with, but not so easy.

(h) Small, Autonomous Vehicles for Intelligence Gathering and Direct Attack:

-- It will be possible to buy commercial IT products with the capability of making autonomous vehicles of sorts – rather than worry about something large one could make a lot of small things – like artificial rats or bats. These could be programmed to infiltrate a wide variety of installations for either intelligence gathering or for direct terrorist activity, like releasing a toxin, etc. A relatively small country or well-funded organization could set up a factory and mass manufacture thousands or even hundreds of thousands of such rats or bats—or they might just buy existing toys and modify them for their own use. These could be used to overwhelm the defenses of an installation. The issue here is that inexpensive technology can be used to asymmetrically attack the US and US interests, and that trying to defend against this small stuff could be extremely expensive. We are going to have to have even more advanced technologies to combat these types of terrorist threats.

-- I agree with the point that suggests that inexpensive nano-based autonomous systems could be used to obtain information from our forces without our knowledge.

-- The "bats" and "rats" made from parts of toys is more plausible, and fully consistent with the view terrorists will use the tools that are widely available.

-- Yes, can be a significant threat. However, this requires significant infrastructure to create. The US should have their own effort in this, and it should be a very high priority.
-- The ability to manufacture large volumes of “smart dust” (or larger rat-sized devices) to provide intelligence gathering capabilities would clearly be a great advantage to whichever side was able to do it. The U.S. should be able to maintain an advantage in this area by continued aggressive research funding.
-- “thousands or even hundreds of thousands of such rats or bats” - kludge solution

(i) Improved Communications Capabilities:

-- Anyone who is interested should have instant global communications, and the ability to coordinate actions across large areas. Huge amounts of current information beyond just weather should be available to all.
-- Google

(j) Continued Use of New or Improved Consumer Products:

-- As they use cell phones and computers today.
-- If information, made more globally available through application of nanotechnology to IT, is used for purposes other than those intended, we could see terrorists or other threats using modern technologies against us.
-- I think the most likely will be the diversion of something commercially available to terrorist purposes – just like the terrorists did not build missiles or bombs, they just took existing jets. They won’t bother to create anything new – they will buy whatever is available and use that.
-- The greatest threat is terrorists will use that which is ubiquitous against us, just as terrorists use cell phones and computers today.

(k) Foundry-Made Unreliable Chips or Hardware Components:

-- N/A

(l) Hardware Viruses and Worms:

-- Capable of bringing down large-scale systems.
-- N/A.

(m) New, Small-Group Business Models and Capabilities:

-- N/A

(n) Increased Chemical Threats:

-- At the same time the US is developing countermeasures such as taggants to help mitigate this threat.
-- N/A

(o) Modification of Commercial Manufacturing:

-- The ability to modify existing commercial manufacturing processes to subvert security will pose a significant threat. A variety of “back doors” could be built into hardware that would then create an opportunity for an enemy to compromise our military systems. Two obvious approaches would be degrading performance of defensive systems simultaneously with an attack, or using longer term covert monitoring (which would not need to reveal the compromise in order to benefit an enemy).

(p) Increased Environmental Threats

(q) Biotechnology Terrorism:

-- While not necessarily an IT issue, nanotechnology may have a large role to play in making bio-terrorism more available to terrorist organization. The opportunity here is engineering of biological agents and delivery systems through nanotechnology.

(r) Tagging/Tracking Algorithms or Cryptographic Schemes:
-- As we utilize more sophisticated tagging and tracking algorithms or cryptographic schemes, the terrorist adversaries study our tactics and learn from them – quickly and responsively. Therefore, we should expect that any new IT tool we develop to engage the terrorists will be turned against us in due course. More emphasis on our part to make hard to detect and hard to decipher codes and technologies can delay the time that these technologies can be turned against us. A good strategic policy to consider is how we will engage our partners and competitors in nanotechnologies for IT in order to achieve this goal of hard to detect and decipher. The arguments can be made from a monetary point of view that would encourage all parties to work very hard to protect their information – and thus protect it from terrorists and us. Which in turn means that we will have to become even better and more knowledgeable about nanotechnologies for IT to understand how we and others utilize it.
(s) Weaponized Distributed Network Platforms:
-- Could be strong threats against our communications networks, information gathering and dissemination networks, and energy grid – as stated above.

Section C. Proper Sector Roles and Responsibilities – Defense versus Commercial

Topic #8: The areas of nanotechnology R&D relevant to future IT capabilities envisioned to be driven by the commercial sector and global marketplace.

General Comments:
-- The global market place tends towards unregulated delivery of IT infrastructure. Such an open approach is unlikely to be consistent with the USAF and DoD needs. The commercial market will drive technology performance and reductions in cost.
-- I agree that all listed topics will be pursued commercially. It is obvious that improved hardware for computation will receive a huge investment from industry. The hope is that, in this case, nanotechnology will solve the vexing problems when scaling logic and memory to under 25 nm. However, this industry investment in new devices and materials for scaled logic may slow down and be diverted if translation of the many nanotechnology ideas into product does not happen within the expected Moore's Law predicted timeframe.
-- Faster, lighter, cheaper technology.
-- I think that this section has been well covered. The commercial and global markets will continue to drive IT solutions into the nanoscale. This will likely be true for faster processors, memory devices, storage devices, and displays.
-- The global market will drive nanotechnology R&D in all of these areas which can be utilized in some fashion by the USAF. But the age old problem is that the global market has different requirements and specifications than are needed for the DoD and so more specialized applications will draw off the global market but require a separate infrastructure to develop. I believe this is definitely true for hardware, but can be extended to software as well. For example, software protection and cryptographic algorithms will be developed for consumer use, but military specifications must be more stringent to ensure that information is not compromised. At the same time, the Air Force will want to be able to track and decipher information which is well protected by our

adversaries – including terrorist organizations. Terrorist organizations may be sending information that would be best recognized by Air Force personnel as potential threats or strategies against the Air Force assets, and so the Air Force will need to be involved in the analysis of this information.

-- The commercial sector will continue the drive to "smaller, faster, cheaper" devices for information technology. The drive for smaller and faster transistors for information processing is nearing its end, but R&D in search of newer devices, suited for further miniaturization, is gathering momentum. New memory devices and mass storage devices (such as IBM's Millipede) will also support the drive to "smaller, faster, cheaper." The large-scale application of these devices in IT, plus the competitive advantage that comes from making them smaller, will be the economic driver for continued improvements in nanofabrication technology. The tools and processes of nanofabrication technology are being used to build a widening array of other products – sensors, medical diagnostic arrays, communications devices, and others mentioned by various respondents. The associated markets for these products are not large enough to *drive* improvements in nanofabrication. Rather, these products are being enabled by improvements in nanofabrication.

(a) Devices and Tools to Solve Bottlenecks with Scaling Reduction:

-- The commercial sector will continue to drive Moore's Law. As they reach the limit on traditional silicon manufacturing processes, they will likely turn to various forms of nanotechnology to keep this trend progressing. Areas for exploration include quantum computing and molecular computing, both working on length scales much smaller than the scales currently in use in today's computers. This research will give us smaller, faster processors.

(This research will give us smaller, faster processors.)

-- The commercial sector will continue the drive to "smaller, faster, cheaper" devices for IT. The drive for smaller and faster transistors for information processing is nearing its end, but R&D in search of newer devices, suited for further miniaturization, is gathering momentum.

(I agree with all, except the conclusion that it will work. This has yet to be proven. Although the research is very valuable and needs to be pursued, NEVER underestimate the difficulty of integration. This may well not work at all.)

(b) NVRAM and Other High-Density Memory:

-- The IBM Millipede project is aimed at mass storage using an array of Scanning Probe Microscopes (SPM). Evolutionary improvements of such a device would push resolution of the SPMs to finer and finer feature sizes, ultimately driving research towards molecularly precise modifications of surfaces.

--The use of CNTs for NVRAM (see, for example, proposals by Nantero) is another area where current research offers the possibility of high-density memory and evolutionary improvements would push manufacturing technology closer to fundamental limits.

-- There is already enormous commercial R&D activity in new non-volatile memory devices which will compete in the most rapidly growing piece of the entire memory and data storage market.

(Absolutely.)

(c) Continued Doubling in Performance (Price, Speed, Size) of Semiconductor Chips Every 18 - 24 Months [i.e. Moore's Law]: (combined w/ (a) Nanodevices to Solve Predicted Bottlenecks with Scaling Reduction)

-- The global market will drive to keep the rate of progress in IT at its traditional Moore's Law rates. This is because the entire infrastructure is based on the fact that old IT systems become obsolete in three years and need to be replaced. Nanotechnology will be the key factor in being able to achieve these goals.

-- Metrics will change.

(d) Larger, Faster Memory Devices:

-- Less % of overall system

(e) Faster, Denser Data Storage:

-- Less % of overall system

(f) Telecommunications:

-- It is estimated that currently the world-wide expenditures on telecommunications is $2 trillion. And so, from this it is clear that this area of technology is driven by the commercial sector and that will continue.

-- Less % of overall system.

(g) Advanced Sensors:

-- For first responders and protection/detection of public places with a focus on low probability of error. (These will not require greatly autonomous systems and so may not require nanotechnology.)

-- There is a lot of development of biosensor technology being driven by commercial interests in health care and medicine.

-- There is a lot of development of biosensor technology being driven by commercial interests in health care and medicine.

-- Growing %.

(h) Nanoelectronics Components and Devices:

-- Will find widespread application in consumer electronics including computers, audio and imaging systems. Many of these systems will be highly integrated. For example, you can hardly buy a cell phone today without a camera. Future devices will be more integrated, extremely powerful, and less conspicuous.

-- Nanoelectronics for computers and telecommunications will be driven by the commercial sector and global marketplace.

(i) Heterogeneity in IT Platforms:

-- By 2020—Driven by the need to create new capabilities and market opportunities, especially individualization of systems, as conventional CMOS scaling (and with it, the brute-force performance improvements) runs out of steam.

(j) Electronic-Biological Convergence:

-- The diagnostic, point-of-care, and medical applications will fiercely drive the underlying technology, albeit with a medical focus. This foundation will quickly enable the extensions into security and bio-electronic interfaces.

-- May take much longer to attract substantial investment from industry; yet these are important technologies.

-- So we leave it to the MD's to develop future IT spinoffs.

-- The diagnostic, point-of-care, and medical applications will fiercely drive the underlying technology, albeit with a medical focus. This foundation will quickly enable

the extensions into security and bio-electronic interfaces. I think this area will grow very quickly.

(k) Lighter, More Compact Computer Displays

(l) Smaller, Better Communication Devices

(m) Micropower Sources:

-- Smaller, more efficient energy sources.

-- May take much longer to attract substantial investment from industry; yet these are important technologies.

(n) Optical and Audible Communications

(o) Logic Circuits for Decision Making

(p) Bioinformatics:

-- A major area that can be driven by commercial sector and global marketplace.

(q) Health/Nanomedicine:

-- New and emerging technologies will be in the field of health and nanomedicine. Energy (hopefully) will be next.

(r) Drive Technology Performance and Cost Reductions (Extracted from General Comments)

-- The global market place will drive IT improvements in terms of capability to cost ratio at exponential rates for many decades into the future. This will dramatically improve existing capabilities of all types – especially military platforms. There will also be some qualitatively new products that will emerge that no one has predicted to date. This will happen, whether the US participates or not. We as a country have the choice to lead or to cede – right now, the rest of the world is gaining ground rapidly.

-- Commercial technology is driven first by cost (Moore's Law is really an economic observation that by reducing transistor size, more chips can be built on a give wafer at a fixed cost point).

Topic #9: The USAF mission elements most impacted in 2030 by advances in nanotechnology in IT.

General Comments:

-- The question is difficult to answer because of the significant probability of pervasive change in many of the underlying assumptions. As one example, extrapolation of present trends in computer power suggest that by 2030 we will have hardware as computationally powerful as the human brain. (No- apples v. oranges) If software advances can take advantage of this capability, systems able to outthink humans on the battlefield will be available. This shift will change how we recruit, train, and deploy the remaining human elements of the USAF.

(Excellent comment – I agree completely.)

-- Capabilities once thought of as expensive and only available to large organizations (USAF) will be available to anyone with a few dollars. These could include advanced radar, and multifunctional materials with embedded electronic sensor systems.

(Yes)

(This is also very true and important. One may be able to purchase commercial chips with which one could assemble active radar cloaking systems, giving them the ability to

build stealth objects. If these are mounted on platforms that are already small, such as a toy airplane, they could be nearly impossible to detect.)

-- By 2030, one may expect a significant degree of maturation of nano-device scaling within IT systems. The unknown is which specific technologies will be winners and which are dead-ends.

(Yes)

-- The ability to understand, control, and manufacture microelectronics will continue to be a foundation of our national security. This is especially true for the Air Force, whose high performance fighters, for example, can only be flown under computer control.

(Yes)

-- I agree that all of the mission elements mentioned in this section will be impacted. However, of those mentioned, I think that a) through d) are the major USAF mission elements that will be impacted by advances in nano-IT by 2030. The trends of unmanned systems, autonomous control of today's piloted aircraft, and better ability to do remote sensing are likely to continue. All of these areas require much improved IT systems in addition to other technological advances such as improved sensors. Information dominance is clearly a key area that will be impacted by nano-IT.

(a) Smaller, Autonomous Vehicles:

-- Miniaturization and multifunctional materials with embedded electronic sensor systems will lighten aircraft and lead to more sophisticated generations of micro- (maybe nano-?) air vehicles.

(Agree – this is not nano (perhaps, in lower power due to NVRAM), but critical.)

-- The advances in computation power and communications will also enable highly adaptable, robust, unmanned systems. This will remove the pilot from many current missions; however, verification and security vulnerabilities in computer hardware and software will need to be addressed.

-- Autonomous systems (sensors and vehicles) will change the way we fight. However, we must be able to manage, fuse, analyze, interpret, and RESPOND to the huge amount of data that will be collected. If we meet these challenges (and I believe that we will) we may then become so dependent on these autonomous systems that this dependency in turn may lead to another vulnerability.

-- The greatest impact will be in the ability to gather more information and pinpoint threats by using autonomous aerial vehicles with ever-increasing sensing, computing, and communicating capabilities as a result of embedded nanotechnologies.

(b) Ability to Replace Traditional Pilots with Better Remote-Pilot-Assist Systems:

-- This trend is already evident, but the capabilities of the supporting IT systems will be greatly enhanced by continuing developments in IT hardware.

(Yes, to integrate with sensors.)

-- The IT advances of the next 25 years will enable a revolution in aircraft and systems. By taking the pilot out of the airplane, the power to mass ratio will be much larger, the volume of the aircraft will be much smaller, the speeds and accelerations will be much larger, and the radar cross section will be much smaller. The airplanes really will fly themselves – their operators will give general directions and receive confirmations of orders and missions accomplished.

-- The power of microchips will enable highly autonomous unmanned systems. The needed for manned aircraft will be reduced.

-- Again, not nano, but VERY important.
-- The scenario of IT advances enabling a revolution in aircraft and systems – taking the pilot out of the plane, is entirely plausible. Almost any reasonable extrapolation of trends in performance, power requirements, and compactness of IT systems supports a scenario where the planes fly themselves with human operators providing general directions and receiving confirmations of results. Likely improvements in understanding and replicating the mechanisms of pattern recognition and cognition will support this scenario as well, but this is a matter of finding better "algorithms" and is not directly linked to progress in nanotechnology.

(c) Remote Sensing:

-- The impact of this technology will be both positive and negative. The USAF will have the ability to monitor virtually the whole world in real time. However, our adversaries will also have, in part, the ability to monitor us. Because there is only one superpower-much of the world may feel that we are their adversary.
(Political, not here)
(Implying that the US will be the only one superpower and much of the world may feel that we are their adversary has two parts that I question. One is the assumption that in 23 years the U.S. will be the one and only superpower. The second is that much of the world today may feel that we are their adversary. We don't know what the situation will be in 2030.)
-- Low-cost massively distributed sensors (in addition to a conventional embodiment, a blue-sky idea is animal (or insect)/electronic hybrids, utilizing biopower for mobility, system power, and communication) will impact personnel/facility security and surveillance.
-- Might be done by swarms of sensors, whether from many, small satellites, from swarms of radar systems, or other reconfigurable sensor systems. Taken globally, this could result in a worldwide sensor web. Improvements in on-board computing of these systems may be able to process the data on-the-fly and provide more information, rather than lots of data that needs to be processed, to the end user.
-- Perhaps the only real nano thing here – via nanosensors.
-- The scenarios involving remote sensing by swarms of redundant, networked sensors (satellites, radar systems, etc.) is also convincing. This is the sort of thing that is made possible by the drive toward "smaller, faster, cheaper" in IT. Such systems will be a lot harder to destroy than their current counterparts.

(d) Command and Control:

-- The Air Force will have a huge number of unmanned aerial vehicles and the information gathered by them will need to be semi-automatically collected and evaluated, and prioritized. IT will play major role here.
-- Command and control (including autonomous systems) is most impacted by revolutions in systems and software for information assessment, information security and miniature autonomous sensing for information gathering. Most of the other items listed are drill-down topics in support of these command and control needs.
-- The command and control chain will be radically streamlined. The role of target tracking, ID, and kill will need to be compress to a single (ideally on-board) decision point that will exploit high performance processing and adaptable sensors.

-- I think the main issue will be force multiplication by taking human beings out of machines and making them part of a remote command and control system. There will be a huge amount of information available, but decisions will have to be made in real time to counter threats. In many cases, the response will have to be automatic – there won't be time to go up a chain of command to receive orders about how to respond. There will be mistakes.

(e) Better Military Planning

(f) Air and Space De-confliction

(g) Controlled and Guided Munitions Systems

(h) More Accurate Guidance Systems

(i) Air Delivery Systems:

-- Augment capabilities and performance, but not necessarily change it

(j) Space-Based Systems:

-- Spacecraft capable of on-board decisions.

-- Impacted by the fact that nanotechnologies are smaller and lighter, and therefore reduced cost of deploying systems

-- New nanoscale phenomena exploited to permit decreased need for cooling or shielding, thereby reducing deployment cost

(k) Cyberspace:

-- The growing US dependence electronics and IT devices creates vulnerabilities from adversaries that will have IT technologies as capable as ours causing an endless duel of counter-countermeasures.

(l) Fundamental Changes in Manufacturing Technology:

-- Greater precision, greater flexibility, lower cost, and more rapid manufacturing.

(m) IT Infrastructure Verification and Security Issues:

-- The USAF, and the DoD in general, will need to address these issues specific to their mission. The ability to access trustworthy hardware and software will be essential.

(n) Information Dominance:

-- One can envision better, information reaching the commanders, pilots, etc. faster, the result of nanotechnologies applied to processors and the shrinking of conventional devices such as sensors.

(o) More Capable Surveillance

(p) Improved Target Tracking and Identification

(q) Progress in the Cognitive Sciences:

-- Nanotech-improved IT systems may also enable capabilities such as super-human artificial intelligence which may offer advances in human-machine interfaces, more automated flight control systems, etc.

(r) Faster, More Efficient Scheduling of Assets

(s) More Responsive Anti-Jam Capabilities

(t) Military Encryption/Decryption:

- Quantum information processing may be a step to greater decryption capabilities, and it may be based in nanotechnology.

-- While computational advances will enhance the cryptographic capabilities of the cryptanalyst, on balance greater computational power is likely to benefit those who encrypt and decrypt information, rather than those who seek to break encryption systems. This is because encryption and decryption complexity scale linearly with computational

power. When computers are ten times more powerful, you can spend ten times the computational effort to encrypt a message. Cryptanalysis, on the other hand, is thought to scale exponentially with the key size used to encrypt a message (for well designed cryptographic systems). If a cryptographic key goes from 64 bits to 128 bits, cracking the encryption will become 2^64 or ~10^19th times as difficult.

(u) Algorithms for Pattern Recognition

-- Largely independent of developments in nanotechnology, the gradually improving understanding of the algorithms for pattern recognition in the brains of humans and other organisms may, by 2030, allows the implementation of pattern recognition (i.e. target acquisition) software and hardware solutions that are superior to the best human capabilities.

(v) Molecular Computing

Topic #10: The policy issues senior USAF leaders should tackle to enable the full potential of nanotechnology-enabled IT capabilities in 2030.

General Comments:

-- Pick a few areas and invest enough resources.

(Can't do that—all eggs in one basket. Really need greater resources so can have many baskets- if relying on technology to give us the edge)

(Even if this means less people funded. Sufficiently funded, long-term research is critical for blue-sky payoff. The same $ spread over many more at a subcritical level produces less, or lower quality.)

-- One response in question #10 above implies in 2030 that the US will be the only superpower. There is no law of physics that says we will always be the superior power in the world. Military superiority will depend not only on our technological edge but on a world class economy able to project political will and of course to generate wealth to pay for weapons systems and development. Much of our economic health in 2030 will depend on our ability to innovate relative to the rest of the world. As indicated in several responses, a significant portion of military investment in R&D in nanotechnology, IT, and other critical areas such as microsystems must shift to long-term strategic investment.

-- Identifying those research areas of interest to USAF that will not be addressed by large commercial interests is very important. Identifying critical components that should be built in trusted foundries is very important, and urging the government to invest in such foundries sounds reasonable and feasible. I do not think the USAF by itself can strongly impact broad societal issues such as support and funding of basic research, US production of engineers with advanced degrees, retention of major manufacturing facilities in the US, and so on. The US government can make a difference, in such matters, and USAF leaders can make their voices heard in the government.

-- I think that point e) sums it up well, i.e., the USAF and DoD in general should tackle a foreseen dependence on foreign electronics and IT services by 2030. As part of this, other elements come into play such as point d) reinstating DARPA's advanced research mission, point f) ensuring that the U.S. is capable of supplying key nano-IT elements and not be dependent on foreign technology, point g) ensuring that the U.S. continues to have micro/nano-IT manufacturing capabilities, point h) ensuring that the USAF advocate and sponsor research in advanced IT technology, and point m) facilitating technology transfer

for capabilities developed in the U.S. I also agree with the other policy items mentioned but they seem to be less critical.

(a) Allowable Level of Autonomous Decision-Making to Produce a Given Effect:

-- Greater levels of autonomy could lead to a more responsive strike force, but could also end up contradicting intended policy, inadvertently. Greater levels of autonomy will require more nano-enabled technologies in information gathering, analysis of information, communication, decryption, encryption, and distribution of information-gathering systems.

-- One of the two most important policy areas that the USAF can tackle to enable the full potential of nanotechnology-enabled IT is: levels of autonomous decision making that the USAF is willing to live with (and the consequences of autonomous decision making). Right now, I don't believe this issue has been thought out by the top leaders in the DoD.

(b) Facilitate Desired Mission Model:

-- The USAF is interested in focusing on the real-time acquisition of data, turning that data into information, and based on that information reaching decisions for developing courses of action. We need to be able to take these courses of action and simulate the effects of following each of these courses, to arrive at what is the best course of action to take. Policies must play a part in arriving at this best course. This analysis is in fact a cognitive approach, which will be possible with the advancements that are expected through the advancements in computing power in this time frame.

(c) Create New R&D Organization:

-- Specifically focused on long-term, high-payoff research. This should include research into more effective methods of funding research ("meta research") as well as research focused on the fundamental limits of manufacturing—limits that are likely to be approached very closely by future manufacturing systems, particularly including the manufacturing systems required to make future molecular computers.

-- The advice to start a new R&D center to focus on long-term issues such as the fundamental limits of nanomanufacturing sounds like a waste of money. Microelectronics manufacturing generates hundreds of billions of dollars a year in revenue, and the industry employs large elite teams of engineers and scientists to engage in cutthroat competition to push the limits of precision in nanomanufacturing closer to the atomic scale every year. Good luck trying to make a difference there!

(d) Reinstate DARPA's Advanced Research Mission:

-- Get DARPA back into doing advanced research, instead of incremental improvements with 18-month timelines.

-- Absolutely. <u>The funding system for risky, blue-sky research in the US is broken.</u> The NSF has low probability (<5%) with subcritical (<$100K/yr) funding – it is no longer worth the effort. Industrial research labs essentially no longer exist, and it is doubtful they will ever come back due to the present economic models. DARPA used to be the last bastion – but no more, with very targeted projects, and no sustainability.

(e) Dependence on Foreign Electronics and IT Services:

-- Globalization does not provide the US with trusted foundries and secure technologies.

-- The USAF should also advocate for government support for critical technologies such as microelectronics and IT to ensure on-shore access to critical leading edge components.

(f) Promote Environmental Conditions to Grow Technology Workforce:

-- USAF needs will be met by specific and unique applications of the general IT that will be developed. To this end, the USAF and their suppliers will have to have people educated in how to utilize the technology to build the autonomous aircraft, etc. It makes sense that such work should be done in the US by American citizens. If the US does not step up and create the environment necessary for people to thrive in IT careers, there won't be any American citizens who can do such jobs. What do we do then—contract the work out to China?

-- Foreign governments are reaching out to multinational companies to convince them to do more of their manufacturing and R&D in their countries. In responding to their shareholders, the companies are allocating their assets where they can achieve the largest returns on their investments. More and more, this means moving over seas—not because things are cheaper there, because when looking at all the costs, they are not. It is because that is increasingly where the infrastructure and the talented people are. It is entirely possible that many of the large multinationals could become effectively Chinese or Indian-based companies if current trends continue.

-- The USAF should advocate for improvements in the technical work force to including work visas for outstanding students studying in the US who have corporate sponsorship for hiring.

(g) Support for Emerging Manufacturing Technologies:

-- Key micro/nanofabrication IT technologies are offshore, which remains a strategic concern. This will not stop, but can be mitigated through greater support in the U.S. for emerging manufacturing technologies (e.g. micro/nano scale assembly) that may provide a strategic advantage. Perhaps more important, such manufacturing support should be then allowed to be leveraged by researchers to accelerate inroads into systems integration.

-- While computers are the most obvious example, a wide range of products would benefit from manufacturing techniques that provide low-cost manufacturing with molecular precision.

(h) Long-Term, Fundamental Research Advocacy:

-- The USAF should advocate for and sponsor continued research in advanced IT technology (electronics, communications, software) both within the Air Force and across the US to insure the USAF and the country has access to the top scientist and engineers along with the resulting technology. We should not allow our country to become second tier in any of the critical IT areas so we can maintain our military and commercial strengths.

-- Absolutely push our government to fund physical science, math and engineering education and research at appropriate levels—at this stage that means quadrupling the 6.1 (basic research) budgets of the services, NSF and Department of Energy basic science over the next decade. The cuts in 6.1 funding for universities is devastating our engineering schools—this is really the most important investment our military can make in our future.

(This is not just academics making self-serving arguments – this is the "Gathering Storm" report.)

-- The one thing that USAF leaders can do that will most benefit the USA and the USAF in 2030 is to increase support for research by rebuilding the 6.1 research budgets and the infrastructure that went with it. You can always tweak the funding mechanism to

improve the outcome for the military, but without the funding, there is nothing to tweak. Signaling strong support for DoE basic science and NSF research budgets should also be a priority. The traditional strength of the US research establishment was the diversity of funding sources and missions that guided them.

-- Increased research advocacy is paramount (at the DOD labs and of course Universities) if we are going to have any future workforce to support the DOD mission.

-- Greater focus on the fundamental long term research objectives that are of concern to the Air Force would be the most effective approach to insuring that the Air Force maintains its advantage over potential adversaries during the coming decades. These can be broadly divided into software, hardware, and the research process itself.

-- Long-term research into hardware must take into account the fundamental limits of manufacturing, and must seek to approach those limits.

-- The US and the USAF has benefited immensely from past investments in engineering, materials and information technology research and education. The DoD has been a leading advocate for the work in the past, but has not maintained the commitment under growing pressure to address near-term requirements. The USAF should be an advocate and financial supporter for strengthening research and education in these areas. Historically the "knowledge discovery" aspect of long-term research has been funded by the service agencies (ONR, AFOSR, ARO) and the NSF. DARPA has exploited the advances in scientific understanding in targeted research efforts to deliver new capability to the services. This structure should be reinforced by expanding the services commitment to long-term research.

-- The remarkable fact about research is not that we humans can do it well, but that we can do it at all. There continues to be great room for improvement in the research process itself – and we should deliberately target this area and its ability to provide a major multiplicative enhancement to the research agenda.

(i) Increased R&D Focus on Development of Integrated Systems:

-- Instead of discrete device demonstrations, increase R&D focus is necessary on this major impediment and establish of longer-term stable research funding to target this.

(j) New Verification Policies:

- The USAF should acknowledge the vulnerabilities in computer hardware and software and put policies in place to make verification, or at least risk reduction, the responsibility of system developers.

(k) Facilitate Collaboration Between Defense Companies and Nano-IT Development Organizations:

-- Make it easier for defense companies to work with the sources of the nano-IT development organizations. For example, intellectual property (IP) issues are extremely prevalent in the nanotechnology world especially with universities, and these could slow down getting technologies from the lab into military systems. This would need to be done with some kind of legislation that makes for a fairer treatment of IP between companies and universities especially when the company is funding the R&D.

(l) Improve Commercial Off the Shelf (COTS) Product Usage:

-- Tackle the issue of how to harden or customize "civilian" IT systems for military applications. Focus on redundancy and error correction and recovery (cheap, plentiful throw-away components) to achieve needed reliability, rather than very expensive components with individual reliability that is very high.

-- US consumer to demand better quality first. We could force Microsoft to improve with our $$.

-- IT represents about $2 trillion per year in the world economy. USAF procurement and R&D funding is not going to have a broad impact on developments in IT. USAF needs will be met by specific and unique applications of the IT that is developed for high-volume commercial applications. Thus the suggestion to harden commercial of-the-shelf hardware by using redundancy and error correction and recovery, with cheap throw-away components, makes sense.

(m) Technology Transfer:

- Transitioning new ideas to application—very big "Valley of Death" between science/discovery and technology/application. More exploratory funding is needed to bridge this gap.

- Can't stop this development . . . can drive it, accelerate it and stay ahead of adversaries in what you understand and can create and deploy . . . means having strong support for open research closely coupled to internal development and deployment.

(n) Study Effect of Nanomaterials on Environment

(o) Long-Term, Balanced IT Investment:

-- The agencies in the U.S. government tend to migrate together to "jump on a bandwagon" with a large majority of funding in certain technology areas for periods of around 8-10 years, to the exclusion of others. While having extreme focus may appear exciting in the short term, a long-term funding policy for IT should provide for a more balanced investment that considers and incorporates software, systems, devices, materials and manufacturing in parallel. As we look toward 2030, no single one of these areas is THE key problem to solve; they must evolve together. Ramping up and down investments with short-term cycles as is done now is very inefficient.

(p) Create New Research and Procurement Structure:

-- One of the two most important policy areas that the USAF can tackle to enable the full potential of nanotechnology-enabled IT is: creating a research and procurement structure that more effectively transitions new ideas from discovery to application. Right now, I don't believe this issue is one that the overall system is working against.

<u>Topic #11:</u> The best, USAF investments in nanoscience and nanotechnology to enable IT capabilities that perform its mission in the year 2030.

General Comments:

-- The global market will drive ubiquity and high production volumes. The USAF will naturally want the opposite—exclusivity. Partnering with owners of "trusted foundry" capabilities on custom design of integrated circuits for specialized military applications is a cost-effective way to put exclusive capabilities in military IT systems.

-- Working on devices (nanotechnology) will not be effective unless the military can invest at a level comparable to the billions of dollars a year spent by each of the major semiconductor manufacturers just to stay competitive.

("The global market will drive ubiquity and high production volumes. ….Working on devices (nanotechnology) will not be effective unless the military can invest at a level comparable …." Yes & no. For general IT, yes. For specialized apps, or emerging areas (such as bio/chem sensors), no.)

-- Specific funding for areas that the commercial sector might not fund will likely be required, but will also likely be substantially dependent on adaptation of commercial systems. This implies the need for a continued Air Force presence in relevant commercial-sector research.
-- The big-picture visions for 2030 are not tied to success of a particular nanodevice or nanomaterial technology. This underscores the breadth of funding that would be needed to cover all possible "winning" technologies. Thus judicious periodic re-evaluation to expand funding is warranted, while more liberal criteria may be appropriate for any elimination in funding specific technology paths.
-- Invest in key technology areas where the AF has unique requirements not likely to be satisfied by commercial or other means: advancing new forms of computing, e.g., quantum or molecular, that are needed for mission success; nanotech based weapon systems; security; platforms for information gathering, processing and dissemination, e.g., unmanned systems; sensor systems for surveillance; antitamper technology; etc. Invest in bridging the valley of death on those technologies important to the USAF.
-- However, the AF and DoD often have requirements that are much more stringent that those found commercially, e.g., in the need to work at extremes of environmental conditions such as in outer space or in dusty, hot deserts, and in the need to often have radiation tolerant systems. Another area that the AF needs to consider is anti-tamper IT systems which may not be developed in the commercial/global sects.

(a) Systems Integration:

-- Of various nanotechnologies into monolithic platforms for specific military needs.
-- Integration (both multi-physics hardware and HW/SW), systems, software are key investments with certain payoff.
-- Greatest potential pay-off for the investment: integrated platforms to enabled autonomous information gathering and networking systems. I presume the USAF would focus on aerial systems or ground-based systems delivered by air – but a focus group of researchers and practitioners from the field may come up with better ideas.
-- Focusing research on system integration, including the problem of obtaining reliable system performance from cheap redundant commodity parts, should provide value.

(b) Security Capabilities:

-- IT-nano has a huge potential to combat terror—specifically, security as applied to hardware (e.g., the encoding of hard-wires security codes in electronics), goods (e.g., sensors to detect contamination), and personnel (e.g., DNA and biochemical tags for friend/foe, at a distance; and low-cost, distributable explosive sniffers).
-- True, but spin part of the funding problem. System requires spin for success
-- Yes, as distributed sensor systems. This should be the highest priority.
-- The commercial sector is not concerned about malicious intrusions into their hardware and software to the same extend that the DoD should be. The existence of nation states that are determined to undermine our capabilities established a different set of technology challenges than typical commercial security and verification concerns. The DoD should further develop and maintain a focus on technologies to ensure trusted hardware and software.
-- Technology to quantify and ensure thrusted hardware and software.
-- Anti-tamper IT systems.
-- Technology to defend our networks and undermine our adversaries

(c) Research into Nanotechnology-Based Weapons Systems (e.g., Self-Replicating Weapons):

-- It is unlikely that commercial organizations will fund. As a consequence, direct funding of this area by some appropriate governmental funding agency will be required.

-- "Self replicating weapons" needs defining; it sounds threatening and triggers the imagination, but a firm scientific basis needs to be articulated to weigh in against other threats listed. A quick Google search reveals most blogs on the subject are referring to science fiction hype.

-- No, what political climate did this one come from--not from the real world.

-- Very unlikely. The threat here is chem/bio, not nano. It's instructive to find all the mistakes in "Prey."

-- Again, this is not a realistic use of research funds, since the probability is so small.

(d) Advanced, Autonomous Sensor Systems Development:

- The military would benefit from commercial advanced sensor development but would also need to focus on more autonomous sensor systems that may require greater sensitivity per detector, with greater false positives, but more redundancy in sensor to check for false positives.

(Yes, most important)

-- Specialized components such as sensors will not necessarily be subject to the same global economics, and USAF funding of research directed towards development of such specialized components should provide value.

-- Yes, a variant of Security Capabilities. Highest priority, and can actually be started today.

(e) Advancing New Forms of Computing—Quantum and/or Molecular Computing

-- Dr. Jim Tour at Rice University is working on a molecular computer based on a randomly assembled collection of active molecular electronics molecules in very small areas comprising Nanocells. Each of the Nanocells can be programmed to work as AND, NAND, and other logic devices. What is still needed for this system is a programmable Nanocell in a commercially viable package.

-- Quantum computing is intriguing, where guarded investment to attain a feasible roadmap to real systems impact may be worthwhile.

-- Nonsense. These are very far-out technologies, with little potential impact. To be very un-PC about it, the quantum computing folks themselves, when pressed, don't think it will work, and use it as an excuse to do fun physics (which it is); and most people working in molecular computing have abandoned it, when they found out how unmanufacturable it was.

-- Monitor and support national efforts in quantum information science and technology.

-- This approach was never credible, and in fact Tour and Reed abandoned it two or three years ago. Reed is going around talking about the impossibility of this approach, and is instead advocating the use of molecular-semiconductor hybrids as sensors. This sensor idea has a lot of credibility, and is being pursued by a large number of investigators.

-- If there is a lesson from Moore's Law, it's "stick with what works" – that is, photolith & integration/scaling. It'll be pedal-to-the-metal until we hit the brick wall, & then we'll start to do all sorts of work arounds that we never were forced to do - such as low power systems (see what was done when laptops demanded less power consumption? That's

only the tip of the iceberg), multichip modules, different architectures, and perhaps even efficient software.

(f) Enhance Technology Transfer Process:

-- Better bridge gap from TRL 4 to TRL 7—between the lab bench and field.

-- Bridge the "Valley of Death" for technologies important to the USAF.

(g) Greater Basic Research Budget:

-- The first need is simply to encourage a broad base of nano-IT research by increasing 6.1 budgets. DARPA used to do this, but they have practically abandoned all IT research in favor of more fashionable biology research. Within such an improved environment, the most effective approach would be to fund consortia of researchers from US universities, corporate labs and national labs to work on integrated systems together. The challenge is to bring together billions of components with a wide range of materials properties and physical capabilities that can perform a given function. Moreover, the nanoscale nature of these components will mean that they will be highly unreliable.

-- Support for basic and applied research in materials, engineering, applied mathematics, and information technology.

(h) Replicating Systems Research:

-- Biological replicating systems demonstrate feasibility. Artificial replicating systems with enhanced capabilities seem entirely feasible.

-- Nonsense.

-- Not within 25 years (or perhaps even 100).

(i) Radiation-Hardened Computing Devices

(j) Ruggedized Computing Systems:

-- Able to operate over a wider temperature range,

(k) Very Light-Weight Electronics:

-- For flight and space applications and the like

(l) Continued USAF Presence in Relevant Commercial-Sector Research

(m) Secure, Trusted Foundry (Extracted from General Comments)

-- Invest in U.S. nano-IT, e.g., trusted foundries. Help combat the growing foreign nano-IT investments by China and others.

-- The global market will drive ubiquity and high production volumes. The USAF will naturally want the opposite -- exclusivity. Partnering with owners of "trusted foundry" capabilities on custom design of integrated circuits for specialized military applications is a cost-effective way to put exclusive capabilities in military IT systems. The same strategy can be applied to other high-volume components besides integrated circuits.

(n) Long-Term, Balanced IT Investment:

-- Reiterating my response to the last question, a more balanced investment that considers and incorporates software, systems, devices, materials and manufacturing in parallel is needed. The investment in nanomaterials has been enormous in the past 6 years. Investment should continue to mine the area and continue the momentum, but perhaps focusing on centers of excellence, knowing that there is a limited budget.

(o) Better Interaction among Academia, Industry and Government:

-- Invest in the process: Getting industry, academia, and government working together to solve military specific problems.

(p) Education/Training:

-- Support to maintain a core competency in the AF and the country in high performance electronics, photonics, and combined Microsystems (e.g. training and education of AF and civilian staff).

(q) Intelligence Platforms:

-- For information gathering, processing and dissemination

(s) Defect and Fault Tolerance:

-- A significant emphasis should be placed on defect and fault tolerance, the ability of an IT system to function with total reliability even though it has a significant and increasing fraction of defective parts. Such a system should be both relatively immune from environmental degradation and also able to repair itself in real time during high stress use.

(t) Power Sources:

-- Technology to more efficienctly use existing power sources and new concepts for power generation.

(u) Satisfy USAF Higher Performance Requirements:

-- The DoD will always have performance requirements that exceed commercial needs. DoD performance is also related to power budget and form factors. The DoD should continue to invest in leading edge research to maintain a performance advantage.

-- Leverage commercial activity (R&D and production) with focused investments to address AF/DoD unique component needs (e.g high frequency rf technology, high productivity process at low power).

-- Enhancing the effectiveness of the research enterprise is likely to bring great rewards over a multi-decade timeframe. Given the near-term focus of most research, a high payoff option is to deliberately focus on longer-term issues. At the same time, specific advances in computational capabilities will be driven largely from the commercial sector but with an Air Force requirement to adapt commercial devices and technologies to Air Force needs.

(v) Unmanned Systems

Section D. Additional Considerations—Panelist-Derived Questions

1.) Areas that the US does not need to pursue with nanotechnology because other solutions are adequate.

General:

-- Difficult question to answer since I believe all areas and leads should be pursued because we cannot predict where breakthrough events will occur (e.g., using lasers for surgery was not conceived during the development of the laser). In addition, the US must be leaders in each field.

-- Chemistry if not "nanotechnology"

-- This is a difficult question to try to answer because we don't know what will be important in the future. Nanotechnology is such a broad range of technologies that to try and identify those areas that we need not pursue is almost impossible. Nanotech is affecting almost all technology sectors, from computing to communications to medicine, to space exploration, etc. And, new breakthroughs are happening at an astonishing rate in nanotechnology, e.g., the use of nanoparticles in cancer treatment. I think the USAF

would be wise to prioritize nanotech areas but not eliminate areas at this point. One more point. If there is a technology being driven by a global market, we should probably be pursuing at some level.
-- I agree with this comment but note that it may be an interim solution. That is, while you are trying to develop a unique nanotechnology-enabled solution.

(a) Software for Information Extraction, Mining and Decision Making:
-- Existing solutions are NOT adequate in this area, and nanotechnology is not the primary answer.

(b) Microsystems Design and Manufacturing Technology:
-- Existing solutions are NOT adequate in this area, and nanotechnology is not the primary answer.
-- I believe Taiwan will emerge as a leading microsystem manufacturing innovator, beyond CMOS, within the decade.
-- Europe is ahead in many aspects.
-- You may be able to deploy a microsystem solution that will help you learn more about the solution and get you to a 70% solution. The US is mostly ahead in microsystems (including microelectronics) but the technology is driven by a global market and the US may not always be ahead in every area.

(c) Heterogeneous Integration Technology (e.g. Multi-Physics System-in-Package)
-- Existing solutions are NOT adequate in this area, and nanotechnology is not the primary answer.
-- Europe is ahead in many aspects.

(d) Explosives:
-- Mostly because I don't define explosives made with nano-fine powders as "nanotechnology".

(e) Power Generation:
-- Mostly because I don't define for power generation w/nano scale materials as "nanotechnology".

(f) The Whole IT Industry:
-- The nano-IT niche is in sensors

2.) How USAF should take advantage of developments occurring outside the US (in China, Taiwan, Japan, India, etc.) and turn them into comparative benefits.

General:
-- I agree that globalization has many benefits as well as some potential drawbacks.
-- The USAF has already started to take advantage of developments in countries such as Taiwan; note the AFRL nano-materials conference, joint with Taiwan, over the past few years. And, the USAF has been investing, although at a low level, in R&D in Taiwan. China and some other countries may pose a greater threat.
-- I would like to rephrase the question: Are there materials or devices (regardless of whether nanotechnology is involved in their manufacture) that are essential to national defense that will have to be sourced from countries that might not always be friendly toward the US? My guess is that the list is short right now, but that it will grow. Providing such a list to members of Congress might motivate more reflection on the role of the government in creating policies to address the potential security issues.

-- I believe this paragraph is true, and where the US can partner with allies we should, without giving away secrets.

(a) Vigilance—Conduct Constant Assessments:

-- Activities such as ONR-Global, for example, do this for the Navy and DOD.

-- Program(s) to follow nanotech development in other countries.

(b) Encourage Long-Term Partnerships:

-- One goal—to maximize these countries' investment in research here.

-- This is happening piecemeal between individual universities and countries, but this should be broadened at the national scale between agencies (e.g. Europe and US).

(c) Attract Best and Brightest Students and PhD Graduates from These Countries:

-- Provide an environment where they stay to contribute to basic research in the US.

-- This has been done and can continue to be done without sacrificing national security.

(d) Send US Students Abroad to Study in Countries Identified as Having Major Future in High-Tech:

-- A simple scholarship program should be sufficient.

-- We could invest in our US students more and encourage them to spend time in studies outside the US with allied nations.

(e) Make US Systems More Nimble:

-- Trend is the other way around with exponentially growing bureaucracy, slowing down of funding decisions, and awaiting unrealistic claims. The competition is passing us by because they are more nimble.

(f) Graduate Fellowships

(g) Continued Involvement in ITRS Process

(h) Participating in Nano-IT Sub-Groups as Emerge to Stay Abreast with Foreign Developments:

-- Starting to see other international organizations forming in the nanotechnology areas, e.g., under OECD (Organization for Economic Cooperation and Development).

(i) Pursue More Joint Efforts:

-- Way to get more involved internationally.

(j) More Educational Programs in This Country

(k) Study Major US-based Global Companies:

-- Major US-based global companies already manage their R&D investments on a global basis, not because it is cheaper, but because this allows better access to technical developments and markets around the world. USAF may want to study how these companies do it.

3.) How the US can promote academic institutions' continued R&D in IT-based nanotechnology yet preserve US information dominance.

General:

-- Issues are associated with the large and growing number of foreign students, especially graduate students and post docs, many of whom used to stay in the US but now are moving back to their countries and taking the technologies with them. It is also difficult for universities to work in a classified environment with their need to publish to promote their students and faculty.

-- Despite predictions of doom by some respondents, the rest of the world is still in the position of trying hard to figure out how we do it and replicate our institutions and our success. Where is the equivalent of Intel, Microsoft, Apple, or Google in India or China? Yes, China is turning out more and more engineers, but perhaps we should worry more about how many venture capitalists they are producing.

(a) Hire Best and Brightest into DoD and Government Jobs

(b) Re-Invest in DOD Labs:

-- So advancements can be recognized and tailored for DOD applications.

(c) Promote University Research—Incentivize Companies and Universities to Partner Meaningfully to Accelerate Technology Transition.

-- Information dominance will occur with application-specific solutions that are well beyond what university research delivers. Funding to universities maintains the flow of basic ideas, of feasibility of approaches, and of highly skilled researchers ready to implement cutting-edge developments into real systems.

-- If US academic institutions remain in the forefront of academic research world wide, then US information dominance will be best served. We cannot prevent other countries from acquiring new IT, but we can stay ahead if we pursue a program of continued innovation and progress.

(d) Long-Term, Stable Projects

(e) More Joint AFRL-University R&D Projects

(f) Continue to Lead World in Translation of Fundamental Research Results into Successful Commercial Products

APPENDIX 4: DELPHI STUDY PARTICIPANTS

Panelists (11)

Dr. J. Charles Barbour
Deputy Director of the Physics, Chemistry, and NanoSciences Center
Sandia National Laboratories (SNL)
Application Scientist
DOE Center for Integrated NanoTechnologies (CINT)

Bio: *Dr. Charles Barbour is Deputy Director of the Physics, Chemistry, and NanoSciences Center at SNL in Albuquerque, New Mexico. For the last five years, he served as the Nanomechanics Thrust Leader within the Department of Energy CINT at Sandia, and currently he serves as the CINT Application Scientist. While at Sandia, he has led programs in: science-based engineering from Density Functional Theory through circuit-level simulation and modeling, mechanical properties of nanostructured materials, corrosion science, plasma synthesis of materials, ion-beam modification of materials, and ion-beam analysis. He has over 150 publications and 2 patents in the field of materials science. In addition to organizing many conferences, he has presented numerous invited talks both in the US and abroad. He was a Meeting Co-Chair for the Materials Research Society Spring 2006 Meeting, and he serves on the International Committee for the Ion Beam Modification of Materials Conference.*
Dr. Barbour joined Sandia in 1987 after spending one year as a visiting scientist in The Netherlands, where he was hosted jointly by the FOM Institute for Atomic and Molecular Physics (Amsterdam) and Philips Research Laboratories (Eindhoven). He received a BS degree in Engineering Physics from the Colorado School of Mines (1980) and a Ph.D. in Materials Science and Engineering from Cornell University (1986). As a mentor, Dr. Barbour has guided the work of three post-docs, and six PhD and MS level students from the U.S. and the Netherlands.

Dr. Richard J. Colton
Head of the Surface Chemistry Branch
Naval Research Laboratory (NRL)
Director, Institute for Nanoscience—Defense Applications of Nanotechnology

Bio: *As Director of the Institute for Nanoscience, Dr. Colton coordinates and manages highly innovative, interdisciplinary research programs and facilities that operate at the intersections of the fields of materials, electronics and biology in the nanometer size domain. The facilities were designed to exploit and complement the broad multidisciplinary character of the NRL in order to bring together scientists with disparate training and backgrounds to attack common goals at the intersection of their respective fields at this length scale. The objective of the Institute's programs is to provide the Navy*

and the DoD with scientific leadership in this complex, emerging area and to identify opportunities for advances in future Defense technology.

Dr. Colton earned B.S. and Ph.D. degrees from the University of Pittsburgh in 1972 and 1976, respectively, where he performed graduate work in the areas of ultraviolet and X-ray photoelectron spectroscopy. In 1976, he became a National Research Council Resident Research Associate at NRL working on secondary ion mass spectrometry (SIMS). Dr. Colton joined the NRL Chemistry Division in 1977 as a research chemist working in surface chemistry. From 1982 to 1998 he was a Head of the Advanced Surface Spectroscopy Section in the Surface Chemistry Branch of the Chemistry Division, where he directed and obtained funding for R&D programs to characterize materials by electron and ion spectroscopies, determine the atomic and molecular structure of surfaces by scanning tunneling microscopy, develop new methods to measure nanoscale adhesion, friction and mechanical properties of surfaces by atomic force microscopy, and develop novel physical, chemical and biological sensors using electron tunneling and molecular recognition.

In 1986, while on sabbatical as a Visiting Associate at the California Institute of Technology in Pasadena, CA, he built a scanning tunneling microscope and used it to understand the then mysterious, atomically-resolved, imaging mechanism of graphite in air. In 1998, he became Head of the Surface Chemistry Branch in the Chemistry Division, where he directs a highly interdisciplinary research program in surface chemistry and physics. The staff of ~70 people includes government employees, postdocs, contractors, visiting faculty, and students -- the majority hold PhD degrees in chemistry, physics, materials science, and engineering. Major research topics include surface science, nanoscience and technology, nanostructured and electronic materials, chemical dynamics, tribology and coatings, and chemical/biological sensors. In 2005, Dr. Colton became the Director of the Institute for Nanoscience. As Director, he manages laboratory R&D funds totaling $10M and nanofabrication facilities used for nanoscience research.

Dr. Colton has published over 130 technical papers, including ten book chapters and five patents, which have been cited in the literature over 5000 times. He is a member of the American Chemical Society (ACS), Sigma Xi, American Vacuum Society (AVS), American Physical Society (APS), and Materials Research Society (MRS). He was the first chairman of the AVS Division on Nanometer-scale Science and Technology in 1993, former chair of the AVS Applied Surface Science Division, and served on the AVS Board of Directors in 1992-93. He received the 1992 Hillebrand Prize awarded by the Chemical Society of Washington, was elected AVS Fellow in 1995, received the NRL-Edison Chapter of Sigma Xi Applied Research Award in 1999, and won numerous technical publication and technology transfer awards including the Federal Laboratory Consortium Award for Excellence in Technology Transfer in 2001. Dr. Colton also received the Navy Meritorious Civilian Service Award in 2003.

Dr. Gary K. Fedder
Professor of Electrical and Computer Engineering and Robotics
Department of Electrical and Computer Engineering
Carnegie Mellon University

Bio: *Dr. Fedder was born in St. Louis, Missouri in 1960. He received the B.S. and M.S. degrees in electrical engineering from Massachusetts Institute of Technology in 1982 and 1984, respectively. In 1994, he received the Ph.D. degree in electrical engineering from the University of California at Berkeley, where his research focused on process development, modeling, and simulation for polysilicon surface microsystems. He joined the faculty of Carnegie Mellon University in October 1994 as an Assistant Professor holding a joint appoinment with the Department of Electrical and Computer Engineering and the Robotics Institute. From 1984 to 1989, he worked at the Hewlett-Packard Company on a VLSI integrated-circuit test system and on modeling of printed-circuit-board interconnect for high-speed computers. He received the 1993 AIME Electronic Materials Society Ross Tucker Award in recognition of his work on MEMS digital multi-mode control. His present research interests include surface-micromachined MEMS in standard CMOS processes, physical design tools for MEMS, embedded microsensor packaging, and microrobotics.*

Dr. Shubhra Gangopadhyay
LaPierre Chair Professor
Department of Electrical and Computer Engineering
University of Missouri – Columbia
Co-director of the International Center for Nano/Micro
Systems and Nanotechnology

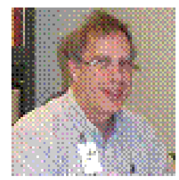
Bio: *Dr. Gangopadhyay is the LaPierre Chair and Joint Professor at the University of Missouri-Columbia's Electrical Engineering, Biological Engineering and Physics Departments. She attained her PhD from the Indian Institute of Technology. Dr. Gangopadhyay is an acclaimed researcher in the fields of material science and physics. Her research interests include BioMEMS, nanoenergetics, PECVD, evaporation, and sputtering deposition of thin-film dielectrics, amorphous silicon, carbon, and silicon carbide films as well as ellipsometry, UV-vis, FT-IR, and current-voltage/capacitance voltage device characterization.*

Dr. Gangopadhyay heads the Gangopadhyay Research Group, an electrical engineering and materials science research facility at the University of Missouri Columbia's College of Engineering and is associated with the International Center for Nano/Micro Systems and Nanotechnology. It is dedicated to expanding the realm of science and technology through optimization of existing techniques and exploration of new dimensions of knowledge. The group's research includes discovering, integrating, and optimizing new materials, processing methods, and characterization techniques. By promoting an interdisciplinary approach, the group's unique and modern research facility - the first of its kind in Missouri - was designed to train, educate and prepare students to join and lead the workforce in innovative solutions to scientific challenges. The group plans to upgrade and expand these high class research facilities over the next two years.

Dr. Ralph C. Merkle
Georgia Institute of Technology
College of Computing, Georgia Tech Information
Security Center

Bio: *Dr. Ralph Merkle received his Ph.D. from Stanford University in 1979 where he co-invented public key cryptography. He joined Xerox PARC in 1988, pursuing research in computational nanotechnology until 1999. Dr. Merkle chaired the Fourth and Fifth Foresight Conferences on Nanotechnology, is on the Executive Editorial Boards of the journal Nanotechnology, was co-recipient of the 1998 Feynman Prize for Nanotechnology Theory, and was co-recipient of the ACM's Kanellakis Award for Theory and Practice, and the 2000 RSA Award in Mathematics. Dr. Merkle has eight patents and has published and lectured extensively. He is a Director of Alcor, and Advisor to the Foresight Institute and Molecular Manufacturing Enterprises, Inc. He has been at Zyvex since 1999, where he continues his nanotechnology research.*

Dr. George O. Ramseyer
Advanced Computing Architecture Branch (IFTC)
Information Directorate
Air Force Research Laboratory



Bio: *Dr. George Ramseyer received a BA and a MA from Binghamton University and in 1983 completed his PhD at Cornell University in analytical chemistry. After one year with the Advanced Surface Science Branch of the Naval Research Laboratory, he joined the Electronics Laboratory of GE Aerospace, where he specialized in the characterizations of microwave and optoelectronic materials and devices. He joined the Reliability Physics Branch at the US Air Force's Rome Laboratory in Rome, NY in 1992, where his research interests were in semiconductor device reliability, focusing on a better understanding of the fundamental causes of electromigration in microelectronic devices. In 1997 Dr. Ramseyer became a part of the Information Directorate of the Air Force Research Laboratory, concentrating on new and developing technologies for information management. Dr. Ramseyer has co-authored over 75 publications and/or presentations. He is a member of the Armed Forces Communications and Electronics Association, the American Association for the Advancement of Science, and the American Chemical Society.*

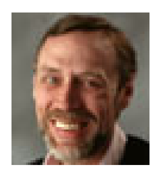
Dr. Mark A. Reed
Harold Hodgkinson Professor of Engineering and Applied Science
Professor of Electrical Engineering and Applied Physics
Yale University

Bio: *Prof. Mark A. Reed received his Ph.D. in Physics from Syracuse University in 1983, after which he joined Texas Instruments (TI) where he co-founded the Nanoelectronics*

research program. In 1990 Dr. Reed left TI to join the faculty at Yale University where he presently holds a joint appointment as Professor in the Electrical Engineering and Applied Physics departments, and is the Harold Hodgkinson Chair of Engineering and Applied Science. His research activities have included the investigation of electronic transport in nanoscale and mesoscopic systems, artificially structured materials and devices, and molecular scale electronic transport. Dr. Reed is the author of more than 150 professional publications and 6 books, has given 15 plenary and over 240 invited talks, and holds 24 U.S. and foreign patents on quantum effect, heterojunction, and molecular devices. He has been elected to the Connecticut Academy of Science and Engineering and Who's Who in the World. Dr. Reed's awards include; Fortune Magazine "Most Promising Young Scientist" (1990), the Kilby Young Innovator Award (1994), the DARPA ULTRA Most Significant Acheivement Award (1997), the Syracuse University Distinguished Alumni award (2000), the Fujitsu ISCS Quantum Device Award (2001), the Yale Science and Engineering Association Award for Advancement of Basic and Applied Science (2002), and in 2003 was elected a Fellow of the American Physical Society.

Dr. Sharon L. Smith
Director of Technology
Lockheed Martin Corporation

Bio: *Dr. Smith is a Corporate Executive and Director of Technology at Lockheed Martin's Corporate Headquarters in Bethesda, MD. Dr. Smith is responsible for research and technology initiatives, including independent research and development projects, university involvement, and various other R&D activities. She is also Chair of the Lockheed Martin's Steering on Nanotechnology. Dr. Smith has over twenty years of experience in management, program management, and engineering at Eli Lilly and Company, IBM Corporation, Loral, and Lockheed Martin Corporation. She has more than twenty technical publications and has given numerous technical presentations in the US and Europe. Dr. Smith holds a B.S. degree in Chemistry from Indiana University, an M.S. degree in Physical Chemistry from Purdue University, and a Ph.D. in Analytical Chemistry from Indiana University.*



Dr. Thomas N. Theis
Director, Physical Sciences
IBM Research, T.J. Watson Research Center

Bio: *Dr. Thomas Theis received a B.S. degree in physics from Rensselaer Polytechnic Institute in 1972, and M.S. and Ph.D. degrees from Brown University in 1974 and 1978, respectively. A portion of his Ph.D. research was done at the Technical University of Munich, where he completed a postdoctoral year before joining IBM Research in 1979.*
Dr. Theis joined the Department of Semiconductor Science and Technology at the IBM Watson Research Center to study electronic properties of two-dimensional systems. He also collaborated in research on surface enhanced Raman scattering, light emission from

tunnel junctions, and conduction in silicon dioxide. The latter work helped to lay the basis for the present understanding of conduction in wide band-gap materials.

In 1982 he became manager of a group studying growth and properties of III-V semiconductors. He published extensively on the DX-center, a donor-related defect which limits the digital performance of some III-V transistors.

In 1989 he was named Senior Manager, Semiconductor Physics and Devices. In 1993, he was named Senior Manager, Silicon Science and Technology, where he was responsible for exploratory materials and process integration work bridging between Research and the IBM Microelectronics Division. While in this position, he was the principal author of IBM's successful contract proposal for the DARPA Low Power Electronics Program.

This fifteen million dollar, three year, industry-university-SEMATECH joint program significantly advanced silicon-on-insulator materials, devices, and design techniques for low-power, high-performance microelectronics. Also while in this position, Dr. Theis coordinated the transfer of copper interconnection technology from IBM Research to the IBM Microelectronics Division. The replacement of aluminum chip wiring by copper was an industry first, the biggest change in chip wiring technology in thirty years, and involved close collaboration between research, product development, and manufacturing organizations. Dr. Theis assumed his current position, Director, Physical Sciences, in February 1998.

Dr. Theis is a member of the IEEE, and a Fellow of the American Physical Society and currently serves on advisory boards for the American Institute of Physics Corporate Associates, the American Physical Society's Physics Policy Committee, the National Nanofabrication Users network, and the National Research Council's Board on Physics and Astronomy. He served as a Member of the Committee for the Review of the National Nanotechnology Initiative, sponsored by the National Research Council. He has authored or co-authored over 60 scientific and technical publications.

Dr. R. Stanley Williams
Senior HP Fellow
Director, Quantum Science Research
Hewlett Packard Laboratories

Bio: *Dr. Stan Williams is a Senior HP Fellow and founding director of the Quantum Science Research group, created in 1995 to prepare HP for the major challenges and opportunities ahead in electronic device technology as features continue to shrink to the nanometer size scale, where quantum mechanics becomes important.*

Dr. Williams' primary scientific research during the past 25 years has been in the areas of solid-state chemistry and physics and their applications to technology. This has evolved into the areas of nanostructures and chemically-assembled materials, with an emphasis on the thermodynamics of size and shape. Most recently, he has examined the fundamental limits of information and computing, which has led to his current research in molecular electronics. Dr. Williams' most recent research has been in the areas of the production and processing of nanostructured materials. He currently leads nanostructures and quantum effects research at HP Labs, with the intention of providing a foundation for the device technology of the next century.

Dr. Williams has received awards for scientific and academic achievement, including the 2000 Julius Springer Award for Applied Physics, the 2000 Feynman Prize in Nanotechnology, the Dreyfus Teacher-Scholar Award and the Sloan Foundation Fellowship. In 2002, he was named to the inaugural Scientific American 50 Top Technology leaders, and the molecular electronics program he leads was named the Technology of the Year for 2002 by Industry Week magazine.

Dr. Williams was a co-organizer and co-editor of the workshop and book "Vision for Nanotechnology in the 21st Century", respectively, that led to the establishment of the US National Nanotechnology Initiative in 2000. Dr. Williams has been awarded 35 US patents with 36 more pending, has published 257 papers in reviewed scientific journals and has written several general articles for technical and business publications. One of his patents was named as one of five that will "transform business and technology" by MIT's Technology Review in 2000. He has presented hundreds of invited plenary, keynote and named lectures at international scientific, technical and business events, including the 2003 Joseph Franklin Lecture at Rice University, the 2004 Debye Lectures at Cornell University, and the 2004 Herman Bloch Lecture (and medal) at the University of Chicago. In addition to his work at HP Labs, Dr. Williams is currently Adjunct Professor of Chemistry at UCLA and of Computer Science at the University of North Carolina at Chapel Hill.

Dr. Williams received his undergraduate degree in chemical physics from Rice University. He attended the University of California at Berkeley from 1974 to 1978, where he obtained his master's and PhD degrees in physical chemistry. After two years as a member of technical staff at AT&T Bell Laboratories, he moved to the University of California Los Angeles as an Assistant Professor in the Department of Chemistry. He was promoted to Associate Professor in 1984 and Professor in 1986. He joined Hewlett-Packard Labs in 1995 to found the Quantum Science Research group.

Dr. John C. Zolper
Director, Microsystems Technology Office (MTO)
Defense Advanced Research Projects Agency (DARPA)

Bio: *Dr. John C. Zolper was appointed the Director of the Microsystems Technology Office (MTO) in March 2005. In this capacity, he is responsible for the monitoring, analysis, and evaluation of research projects directed by the MTO Program Managers. In addition, he is responsible for the conceptual planning necessary to lead MTO into new program areas far in advance of the current state-of-the-art in the areas of electronics, photonics, MEMS, component architectures, and algorithms.*

Prior to being appointed Director of MTO, Dr. Zolper was Deputy Office Director from September 2002. Dr. Zolper first joined DARPA's Microsystems Technology Office in October 2001 as a Program Manager. His program responsibilities included managing the Wide Bandgap Semiconductor Technology Initiative program thrust on High Power Electronics and the Technology for Frequency Agile Digitally Synthesized Transmitters (TFAST) program. He is interested in a range of Microsystems technologies including novel semiconductor devices and circuits, ultra high speed analog devices, wide bandgap electrical and photonic devices, high power electronic components, and photovoltaics.

Prior to joining DARPA, Dr. Zolper was a program officer in the Electronics Division of the Office of Naval Research. At ONR he was responsible for managing the ONR's basic and applied research programs in advanced electronics. His programs included several of the premier academic and industrial teams developing group III-Nitride and SiC electronics.
Prior to joining ONR in 1997, Dr. Zolper was a senior member of technical staff at Sandia National Laboratories in Albuquerque, NM from 1989 to 1997 where he developed advanced III-V semiconductor processes and devices, including the first GaN JFET. In 1988 Dr. Zolper spent time as a post-doctoral fellow at the University of New South Wales, Sydney, Australia working on high efficiency silicon solar cells.
Dr. Zolper was awarded the PhD in Electrical Engineering from the University of Delaware in 1987 and the BA in Physics from Gettysburg College in 1982. He is the author or co-author of over 150 journal and conference papers, seven book chapters, and holds five US patents. He is a Senior Member of IEEE.

Advisors (2)

Dr. Richard D. Averitt
Assistant Professor of Physics
Department of Physics
Boston University

Bio: *Dr. Richard Averitt received a BS in Electrical Engineering from UC San Diego and the MS and PhD degrees in Applied Physics from Rice University. His PhD thesis work, completed in 1998, was for the synthesis and optical characterization of gold nanoshells, a new type of nanoparticle for which Dr. Averitt has two patents. Dr. Averitt was a Los Alamos National Laboratory Director's postdoctoral fellow from February 1999 to February 2001. His postdoctoral work at Los Alamos focused on time resolved terahertz spectroscopy of strongly correlated electron materials. In 2001, Dr. Averitt became a member of the technical staff in the condensed matter and thermal physics group and in 2005 a member of the Center for Integrated Nanotechnologies serving as the thrust leader for complex functional nanomaterials. In 2007, Dr. Averitt moved Boston University Department of Physics. Dr. Averitt's research interests are primarily directed towards developing and applying ultrafast optical and terahertz spectroscopic methods for fundamental materials characterization. Dr. Averitt's interests in characterizing the electrodynamic properties of materials include metamaterials, plasmonic materials, correlated electron materials, and a variety of other of multifunctional materials.*

Dr. Morley O. Stone
Chief, Hardened Materials & Manufacturing Division
Air Force Research Laboratory (AFRL)
Materials and Manufacturing Directorate (MLPJ)

Bio: *Dr. Morley Stone is a principal research biologist with the United States Air Force Research Laboratory. Dr. Stone graduated suma cum laude from Wright State*

University in 1991 with a B.S. degree in biological sciences. In 1992, Dr. Stone entered the Air Force's Palace Knight Program and was assigned the Materials and Manufacturing Directorate of the Air Force Research Laboratory (AFRL/MLPJ). In 1997, Dr. Stone received his Ph.D. degree in biochemistry from Carnegie Mellon University. Dr. Stone's group performs research in the areas of biological infrared detection, biological chromophores, biological inorganic deposition, and polymer-based microfabrication. Dr. Stone received AFRL/ML's Charles J. Cleary Scientific Achievement Award in 1999, received Honorable Mention for the Air Force Basic Science Award in 2000, and was awarded the AFRL Commander¹s Cup in 2002. Dr. Stone's biotechnology team has recently been award Star Team status by the Air Force Office of Scientific Research.

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APPENDIX 5: THE SCALE OF THINGS GRAPHIC

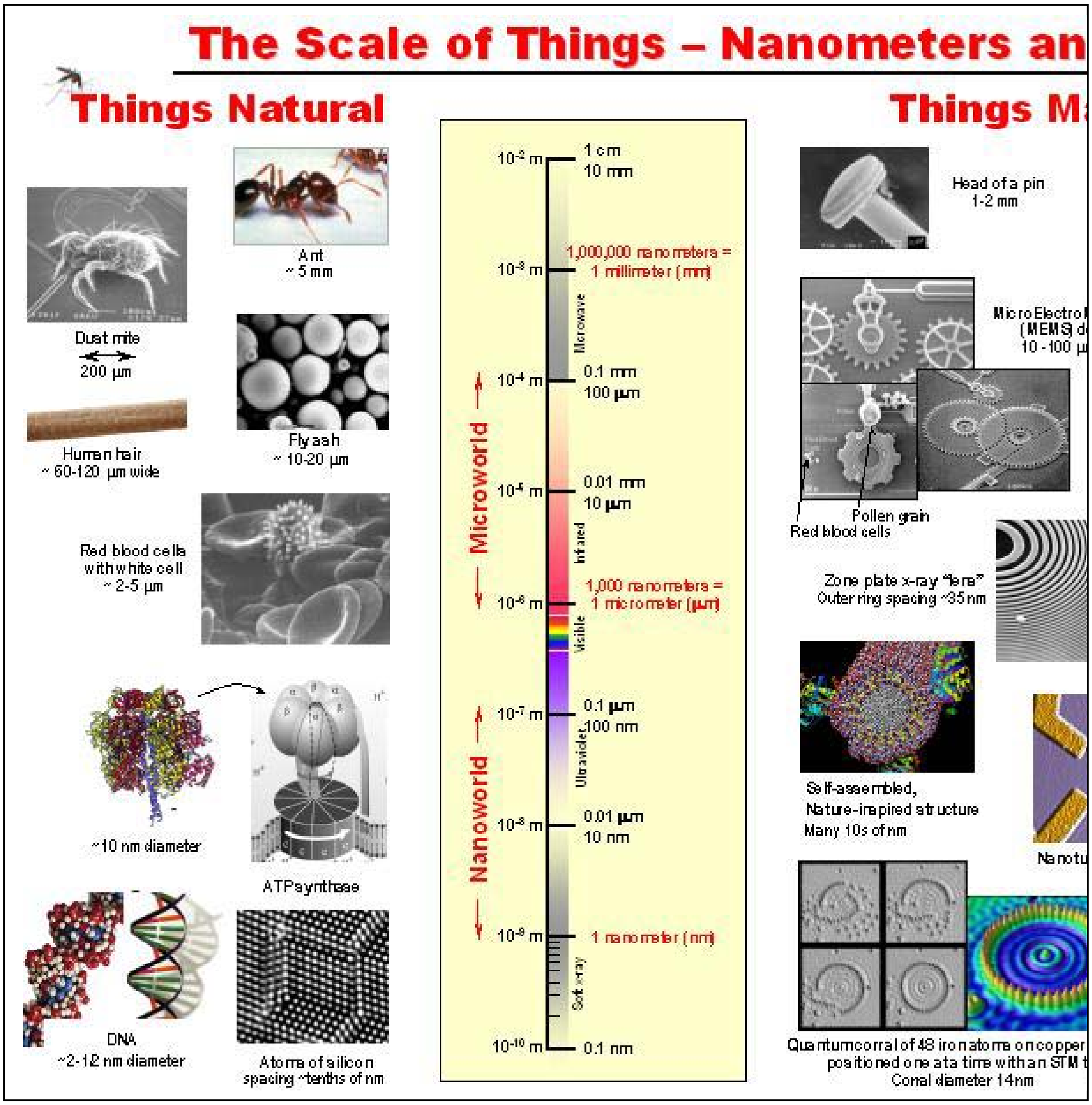

Figure A5.1 The Minute Scale of Natural and Man-Made Things (NNI, 2003, np)

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APPENDIX 6: SAMPLE INVITATION LETTER

Major Joseph H. Imwalle
Air Command and Staff College
225 Chennault Circle
Maxwell AFB, AL 36112-6426

Dr. (Full Name)
(Mailing Address)

Dear Dr. (Last Name):

Thank you for agreeing to participate in the Chief of Staff of the Air Force's (CSAF) Blue Horizons Project. The objective of this major research initiative is to provide key decision makers and planners with a forecast of the emerging technologies that will shape the U.S. Air Force (USAF) and its operating environment in the year 2030. Your input will play a key role in helping the Air Force assess the most probable future impact of nanotechnology in the realm of information technology. The results of this study will be presented to the CSAF and his staff in June of 2007, and will serve as an input for the development of service budgets, war games, the Strategic Planning Guidance, and the Quadrennial Defense Review.

You were hand-picked as part of a highly distinguished panel of subject matter experts from across government, industry and academia. The particular study you will support will use the Delphi Method to collect and synthesize the opinions of the panel members in the pursuit of consensus. Each participant will be asked to respond to two, sequential questionnaires. The first will be sent out on November 29, 2006; the second, on January 10, 2007. The answers from the first questionnaire will be used to formulate the questions for the second questionnaire. For each questionnaire, you will be given three weeks to respond. All responses will be kept anonymous to encourage free and open debate.

The USAF greatly appreciates your support of this research. I look forward to reading your views and ideas on this topic. If you have any questions, please feel free to contact me at (XXX) XXX-XXXX or joseph.imwalle@maxwell.af.mil.

Sincerely,

JOSEPH H. IMWALLE, Major, USAF

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APPENDIX 7: DELPHI STUDY DATA TABLES

Table 2.1 Important Advancements Shaping Today's Nanotechnology in IT Development

Panel Responses	**Agree**	**Disagree**	**No Position**	**Score**
Discovery/Exploitation of New Materials (w/ New Properties)	7	0	4	7
New Algorithms for Data Analysis	6	0	5	6
Microelectonics -- Now Nanoelectronics	5	0	6	5
Plastic Electronics	5	0	6	5
Lithography	5	1	5	4
Optoelectronics	4	0	7	4
Mechanical Microsystems -- Now Nanosystems	4	0	7	4
Instrumentations and Tools	4	0	7	4
Low Power, Nonvolatile Memory	4	0	7	4
New Displays	4	1	6	3
ITRS Planning Process	3	1	7	2
New IT Circuit Architectures *(Round 2 Input)*	2	0	9	2
Post/Beyond CMOS Technologies *(Round 2 Input)*	2	0	9	2
Bio-Based Nanotechnology *(Round 2 Input)*	1	0	10	1

Table 2.2 Important Trends Shaping Today's Nanotechnology in IT Development

Panel Responses	**Agree**	**Disagree**	**No Position**	**Score**
Drive to Miniaturize IT Devices -- Faster/Cheaper/Denser	8	0	3	8
Mobile, Agile Modular Information-Gathering Platforms	5	0	6	5
Increased Information Access and Precision Response Speeds	4	0	7	4
Increasing Amounts of Information to Gather and Analyze	3	0	8	3
Distributed Information Gathering and Decision Making	3	0	8	3
Desire for More Data Storage	3	0	8	3
Desire for More Data Processing	3	0	8	3
World-Wide Cooperation and Competition	2	0	9	2
Greater Precision in Manufacturing	2	0	9	2
Far from Known Limits of Fundamental Physics	3	2	6	1
Moore's Law *(Round 2 Input)*	1	0	10	1

Table 2.3 Emerging Trends for IT-Focused Nanotechnology Development

Panel Responses	**Agree**	**Disagree**	**No Position**	**Score**
Post/Beyond CMOS Technologies	9	0	2	9
Shift from Top-Down Fabrication to Bottom-Up Assembly	6	1	4	5
Heterogeneous IT Integration	5	0	6	5
Neuroelectronic Interfacing	5	1	6	4
Highly Integrated IT Systems	4	0	7	4
Automatic Configurable and Reconfigurable IT Systems	4	0	7	4
Quantum Computing	4	0	7	4

New Metrics	4	0	7	4
Assembly Technology at the Nanoscale	3	0	8	3
Synergy Between Directed Assembly and Self Assembly	3	0	8	3
Random Access Memories	3	0	8	3
Mass Storage Devices	3	0	8	3
Transmission on a Chip and Board Level	3	0	8	3
Sensor Arrays and Imaging Systems	3	0	8	3
Displays	3	0	8	3
Sophisticated, "Context-Aware" IT Systems	3	0	8	3
Photonic Networks	3	0	8	3
Molecular Computing Using Biological System	3	1	7	2
Microelectronics-Chem/Bio Systems Integration	3	1	7	2
The Catalyst of "Nanomedicine"/Bio-Engineering	3	1	7	2
Microwave Communication System	2	1	8	1
Integrated Opto-Electronic Systems *(Round 2 Input)*	1	0	10	1
Improvements in IT Algorithms *(Round 2 Input)*	1	0	10	1
Hybrid Insect/Sensor/Electronic Systems *(Round 2 Input)*	1	0	10	1
Integrated Opto-Electronic Systems *(Round 2 Input)*	1	0	10	1

Table 2.4 Emerging Limiting Factors for IT-Focused Nanotechnology Development

Panel Responses	Agree	Disagree	No Position	Score
Power Dissipation	7	0	4	7
Interconnect Architecture Reliability *(Round 2 Input)*	2	0	9	2
Economics of Manufacturing Process *(Round 2 Input)*	2	0	9	2
Statistical Uncertainty in Placement of Individual Dopant Atoms	1	0	10	1
Defect Resilience *(Round 2 Input)*	1	0	10	1
Heterogeneous, Nanoscale Component Assembly *(Round 2 Input)*	1	0	10	1
Packaging for Molecular-Level Devices *(Round 2 Input)*	1	0	10	1
Heat *(Round 2 Input)*	1	0	10	1
Quantum Computing—Scaling Up to Many Qubits *(Round 2 Input)*	1	0	10	1
Scaling Up Molecular Computers *(Round 2 Input)*	1	0	10	1
Variability Between Nominally Identical Devices *(Round 2 Input)*	1	0	10	1

Table 2.5 Biggest Challenges to Developing IT-Focused Nanotechnology Capabilities

Panel Responses	Agree	Disagree	No Position	Score
Manufacturing/Fabrication	9	0	2	9
Technology Transfer -- From Lab Bench to Field	8	0	3	8
Funding for Long-Term, Exploratory Research	6	0	5	6
Standard Peer Review Process is Broken	5	0	6	5
Integration Capabilities	5	0	6	5
Science and Engineering Training/Education	4	0	7	4
IT Challenges in Moving Along the Scaling Path	4	0	7	4
Implementing Devices and Interconnect at Nanoscale	3	0	8	3
Control and Reproducibility of Nano-Scale Structures	3	0	8	3

Power Generation and Storage	3	0	8	3
Thermal Issues	3	0	8	3
Developing Peripheral Products Needed to Support These Devices	2	0	9	2
Getting Stable Molecular Computers to Work	2	0	9	2
Getting Quantum Confinement Schemes to Work Reliably for Quantum Computers	2	0	9	2
Memory Devices	2	0	9	2
Preconceptions	2	1	8	1
Big Industry Usually Very Conservative *(Round 2 Input)*	1	0	10	1
Interagency Coordination *(Round 2 Input)*	1	0	10	1
Development Highly Capable Sensors *(Round 2 Input)*	1	0	10	1
Handling Anticipated Higher Degree of Structural and Functional Variability	1	1	9	0

Table 3.1 (Most Likely) Nanotechnology-Enabled, TRL-6+ IT Capabilities by 2030

Panel Responses	**Agree**	**Disagree**	**No Position**	**Score**
Orders-of-Magnitude Better Computing Capabilities	10	0	1	10
Smaller, Higher Density Storage	7	0	4	7
Persistent Surveillance Capabilities	6	0	5	6
Optical Communications	5	0	6	5
Enabling Technologies for Sub-Centimeter Vehicles	5	0	6	5
Directed Assembly at the Micro/Nano Scale	5	0	6	5
Nanobiosensor Technology	5	0	6	5
Ubiquitous Connectivity, Largely Wireless	5	0	6	5
Quantum Computers	5	1	5	4
Hand-Held Platform Capabilities for Integrating Nano-Enabled Technologies	4	0	7	4
Remote Creation, Harvesting and Storage of Energy	4	0	7	4
New Approaches to Sensors for Chemical and Explosive Threat Detection	4	0	7	4
Sensing Platforms for Microparameter Analysis of Biomolecules and Pathogens	4	0	7	4
Higher Efficiency Sensors for Radiation and Nuclear Material Detection	4	0	7	4
Single Photon Detectors	4	0	7	4
New Imagery Capabilities	4	0	7	4
Reduced Form Factor Radar-Responsive Tags	4	0	7	4
Low-Power Nanoelectronics	4	0	7	4
Non-Volatile Memory	4	0	7	4
Molecular and Mechanical Self Assembly	4	0	7	4
Parallel Manipulation Systems for Nanoscale Assembly	4	0	7	4
"Smart Dust" Systems	5	2	4	3
Electronic-Biological Convergence	4	1	6	3
Nano-Computers	3	0	8	3
Cognitive Computing	3	0	8	3
Optical Information Processing	3	0	8	3

Advanced Displays	3	0	8	3
New Materials	3	0	8	3
Configurable and Reconfigurable IT Systems on Chip	3	0	8	3
Small, Long-Life Micropower Sources	3	0	8	3
Sources/Detectors at Either End of Electromagnetic Spectrum	3	0	8	3
Anti-Tamper Technologies	3	0	8	3
New Methods for Audio Collection and Processing	3	0	8	3
Totally Autonomous Fighter Aircraft	3	0	8	3
Control and Guidance of Weapon Systems	3	0	8	3
Molecular Computers	3	2	6	1

Table 3.2 (Most Likely) Impacts of Nanotechnology in IT on World in 2030

Panel Responses	Agree	Disagree	No Position	Score
Improved Connectedness—Better and Faster Communications	8	0	3	8
Small, Cheap Sensors	7	0	4	7
Intelligent Weapons Systems	5	0	6	5
Vastly Cheaper Memory	4	0	7	4
Electronic-Bio Sensors and Systems	4	0	7	4
Much Faster and More Power-Efficient Processors	3	0	8	3
More Info Readily Available to Almost Everyone Worldwide	3	0	8	3
Improved Encryption/Decryption Capabilities	2	0	9	2
Improvement of Materials	2	0	9	2
New Business Models	2	0	9	2
Unimagined, Revolutionary Applications	2	0	9	2
Human Health	2	0	9	2
Control Over Weapon Systems	2	0	9	2
New Security Threats	1	0	10	1
"Software-esk" Development Cycle	1	0	10	1
High Storage Systems—Faster, Cheaper, Lighter *(Round 2 Input)*	1	0	10	1
Ubiquitous, Networked Information Gathering *(Round 2 Input)*	1	0	10	1
Much More Efficient and Effective Technologies *(Round 2 Input)*	1	0	10	1
Faster Product Development Cycles *(Round 2 Input)*	1	0	10	1

Table 3.3 Nanotechnology R&D Relevant to Future IT Driven by Commercial Marketplace

Panel Responses	Agree	Disagree	No Position	Score
Devices and Tools to Solve Bottlenecks with Scaling Reduction	8	0	3	8
NVRAM and Other High-Density Memory	8	0	3	8
Advanced Sensors	6	0	5	6
Faster, Denser Data Storage	6	0	5	6
Larger, Faster Memory Devices	5	0	6	5
Telecommunications	5	0	6	5
Lighter, More Compact Computer Displays	5	0	6	5

Smaller, Better Communication Devices	5	0	6	5
Drive Technology Performance and Cost Reductions	4	0	7	4
Nanoelectronic Components and Devices	4	0	7	4
Electronic-Biological Convergence	4	0	7	4
Micropower Sources	3	0	8	3
Health/Nanomedicine *(Round 2 Input)*	3	0	8	3
Heterogeneity in IT Platforms	3	0	8	3
Bioinformatics	3	0	8	3
Optical and Audible Communications	2	0	9	2
Logic Circuits for Decision Making	2	0	9	2

Table 3.4 USAF Mission Elements Most Impacted By IT-Focused Nanotechnology

Panel Responses	Agree	Disagree	No Position	Score
Smaller, Autonomous Vehicles	8	0	3	8
Ability to Replace Traditional Pilots with Better Remote-Pilot Assist Systems	6	0	5	6
Remote Sensing	6	0	5	6
Command and Control	5	0	6	5
Space-Based Systems	3	0	8	3
Military Encryption/Decryption	3	0	8	3
Better Military Planning	2	0	9	2
Air and Space Deconfliction	2	0	9	2
More Accurate Guidance Systems	2	0	9	2
Air Delivery Systems	2	0	9	2
Improved Target Tracking and Identification	2	0	9	2
Controlled and Guided Munitions Systems	1	0	10	1
Cyberspace	1	0	10	1
Fundamental Changes in Manufacturing Technology	1	0	10	1
IT Infrastructure Verification and Security Issues	1	0	10	1
Information Dominance	1	0	10	1
More Capable Surveillance	1	0	10	1
Progress in the Cognitive Sciences	1	0	10	1
Faster, More Efficient Scheduling of Assets	1	0	10	1
More Responsive Anti-Jam Capabilities	1	0	10	1
Algorithms for Pattern Recognition	1	0	10	1
Molecular Computing	1	0	10	1

Table 4.1 Best USAF Investments in Nanotechnology to Enable IT Capabilities

Panel Responses	Agree	Disagree	No Position	Score
Advanced, Autonomous Sensor Systems Development	5	0	6	5
Security Capabilities	4	0	7	4
Greater Basic Research Budget	3	0	8	3
Secure, Trusted Foundry	3	0	8	3
Satisfy USAF Higher Performance Requirements *(Round 2 Input)*	3	0	8	3

Systems Integration	2	0	9	2
Enhance Technology Transfer Process	2	0	9	2
Radiation-Hardened Computing Devices *(Round 2 Input)*	2	0	9	2
Better Interaction among Academia, Industry and Government *(Round 2 Input)*	2	0	9	2
Education/Training *(Round 2 Input)*	2	0	9	2
Advancing New Forms of Computing	3	2	6	1
Ruggedized Computing Systems *(Round 2 Input)*	1	0	10	1
Very Light-Weight Electronics *(Round 2 Input)*	1	0	10	1
USAF Presence in Relevant Commercial-Sector Research *(Round 2 Input)*	1	0	10	1
Long-Term, Balanced IT Investment *(Round 2 Input)*	1	0	10	1
Intelligence Platforms *(Round 2 Input)*	1	0	10	1
Defect and Fault Tolerance *(Round 2 Input)*	1	0	10	1
Power Sources *(Round 2 Input)*	1	0	10	1
Unmanned Systems *(Round 2 Input)*	1	0	10	1
Replicating Systems Research	1	2	8	-1
Research into Nanotechnology-Based Weapons Systems	2	4	5	-2

Table 4.2 Policy Issues USAF Leaders Should Tackle to Enable IT-Focused Nanotechnology

Panel Responses	Agree	Disagree	No Position	Score
Long-Term, Fundamental Research Advocacy	10	0	1	10
Promote Environmental Conditions to Grow Technology Workforce	5	0	6	5
Reinstate DARPA's Advanced Research Mission	4	0	7	4
Dependence on Foreign Electronics and IT Services	4	0	7	4
Support for Emerging Manufacturing Technologies	4	0	7	4
Technology Transfer	4	0	7	4
Allowable Level of Autonomous Decision-Making to Produce a Given Effect	2	0	9	2
Increased R&D Focus on Development of Integrated Systems	2	0	9	2
Improve COTS Product Usage	2	0	9	2
Create New R&D Organization	2	1	8	1
Facilitate Desired Mission Model	1	0	10	1
New Verification Policies	1	0	10	1
Facilitate Collaboration Between Defense Companies and Nano-IT Development Organizations	1	0	10	1
Study Effect of Nanomaterials on Environment	1	0	10	1
Create New Research and Procurement Structure *(Round 2 Input)*	1	0	10	1
Long-Term, Balanced IT Investment *(Round 2 Input)*	1	0	10	1

Table A12.1 Potential Technology Surprises from IT-Focused Nanotechnology in 2030

Panel Responses	Agree	Disagree	No Position	Score
"New-Wave" Attack Capabilities	8	0	3	8
Implications of Overseas Microelectronics Outsourcing	5	0	6	5
Another Country(ies) Overtakes US as Technology Lead	4	0	7	4
Controlled, Light-Weight, More Powerful Warheads	2	0	9	2
Portable Computer Attack Capabilities	2	0	9	2
Self-Replicating Weapons Systems	3	2	6	1
Communications and Computing Technology Based on Quantum Informations Science Maturation	2	1	8	1
Information Gathering and Decryption Breakthroughs	1	0	10	1
Harvesting and Production of Both Energy and Water	1	0	10	1
New, Small-Group Business Models and Capabilities	1	0	10	1
Exploitation of US' IT Security Holes *(Round 2 Input)*	1	0	10	1
Environmental Challenges *(Round 2 Input)*	1	0	10	1
Nano-Enhanced Weapon Systems *(Round 2 Input)*	1	0	10	1
Radar Jamming *(Round 2 Input)*	1	0	10	1

Table A12.2 IT-Focused Nanotechnology Threats Envisioned from Terrorists

Panel Responses	Agree	Disagree	No Position	Score
Cyberattacks on US IT Systems and Critical (Computer-Controlled) Infrastructure	5	0	6	5
Small, Autonomous Vehicles for Intelligence Gathering and Direct Attack	5	0	6	5
Improved Intelligence-Gathering Capabilities	3	0	8	3
Continued Use of New or Improved Consumer Products	3	0	8	3
Biotechnology Terrorism *(Round 2 Input)*	3	0	8	3
Increased Chemical Threats	3	1	7	2
Infiltration of US C4I Networks	2	0	9	2
Encryption Capabilities	2	0	9	2
Improved Communications Capabilities	2	0	9	2
Sophisticated Jamming and Counter-Surveillance Technologies	1	0	10	1
Modification of Commercial Manufacturing *(Round 2 Input)*	1	0	10	1
Increased Environmental Threats *(Round 2 Input)*	1	0	10	1
Weaponized Distributed Network Platforms *(Round 2 Input)*	1	0	10	1
Tagging/Tracking Algorithms or Cryptographic Schemes *(Round 2 Input)*	1	0	10	1
Intelligent Reasoning Devices	1	1	9	0
Foundry-Made Unreliable Chips or Hardware Components	1	1	9	0
Hardware Viruses and Worms	1	1	9	0
New, Small-Group Business Models and Capabilities	1	1	9	0
Self-Replicating Weapons Systems	2	3	6	-1

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APPENDIX 8: IN PURSUIT OF DESIGN AT THE SCALE OF NATURE

There are two different philosophies on building matter to specification at the nanoscale, "top-down" and "bottom-up." The increasingly precise, top-down manufacturing approach is where structures are made by removing unwanted parts of an initial bulk material through cutting, grinding or etching. Silicon-based, nanoelectronics production originates from a top-down approach, extending traditional complementary metal-oxide-semiconductor manufacturing technology methods to the nano-level. Lithography, a top-down method of transferring intricate lines and patterns that define integrated circuits (IC) onto semiconductor materials, is currently the key fabrication technology of the semiconductor industry (Wilson et al, 2002, 195). The bottom-up fabrication model is where custom materials and structures are created by consciously forcing molecular building blocks together. This closely emulates nature which uses a bottom-up approach to create new things one atom at a time while man-made creations are mostly fabricated using a top-down approach.

Many representatives of the nanotechnology community argue that the bottom-up approach is the future. Dr. Kostantinos Glinos, head of the Embedded Systems Unit of the European Commission, believes, "We are unlikely to ever make atomic-scale patterns using today's top-down approach, so we will need bottom-up fabrication techniques, such as self-assembly" (European Commission, 1999, np). Dr. Ottilia Saxl, founder and Chief Executive Officer of the Institute of Nanotechnology, acknowledged, "The individual manipulation of atoms and molecules using man-made tools (such as microscopes) to make larger structures is incredibly time-consuming and inefficient" (Saxl, 2005, 10). *Nanotechnology: Basic Science and Emerging Technologies*, a highly regarded book on

the topic of nanotechnology, asserts, “It is the combination of the understanding gained from biological self-assembly, the chemical development of new molecular structures and the physical development of new tools of nanofabrication that promises to revolutionise [sic] the electronics industry” (Wilson et al, 2002, 191).

Some level of self-organization of materials using the principles and forces of biology and chemistry is expected to play a role in the bottom-up manufacturing paradigm. Control over the arrangement of individual atoms represents the ultimate limit of fabrication—the purist’s vision of nanotechnology. One method using the bottom-up approach is self-assembly, in which molecules or atoms arrange themselves into a structure due to their natural properties (The Royal Society, 2004, 3). This effect can be achieved through chemical synthesis or biological-based assemble processes. Dr. Roger Whatmore, Royal Academy Professor of Engineering, explains, “The self-assembling properties of biological systems, such as DNA molecules, can be used to control the organization of objects such as carbon nanotubes, which may ultimately lead to the ability to grow parts of an integrated circuit, rather than having to rely upon expensive top-down techniques” (Whatmore, 2005, 72). Some researchers believe that self-assembling circuits as a result of nanotechnology could keep the industry chugging for 50 more years (Kanellos, 2005, 2).

Dr. Ted Sargent, an Electrical and Computer Engineering Department Professor at the University of Toronto, theorizes that the real challenge in nanotechnology is "engineering matter at the molecular scale, such that it achieves a needed function" (Lovgren, 2004, 2). Under the guidance of Dr. Horst Störmer, Nobel laureate, “scientists are working to harness molecules' natural ability to bond, assemble and organize into

high-performance, nano-size transistors and sophisticated circuits that will make today's computer chips seem like simpletons" (Helm, 2005, 22). Self-assembly processes also have the potential to be relatively inexpensive methods to shrink electronic chips down to the molecular level which promises to help end the need for multi-billion-dollar, IC fabrication facilities (reference Subsection 2.1 regarding Rock's Law).

Dr. Sargent states, "There is obviously a mismatch between top-down nanotechnology and the bottom-up technique, and an urgent need exists to link the two: we must start digging the Chunnel from each side of the channel such that we meet in the middle" (Sargent, 2006, 151). Figure 2.4 visually depicts this hypothetical convergence of the two approaches to nanoscale manufacturing.

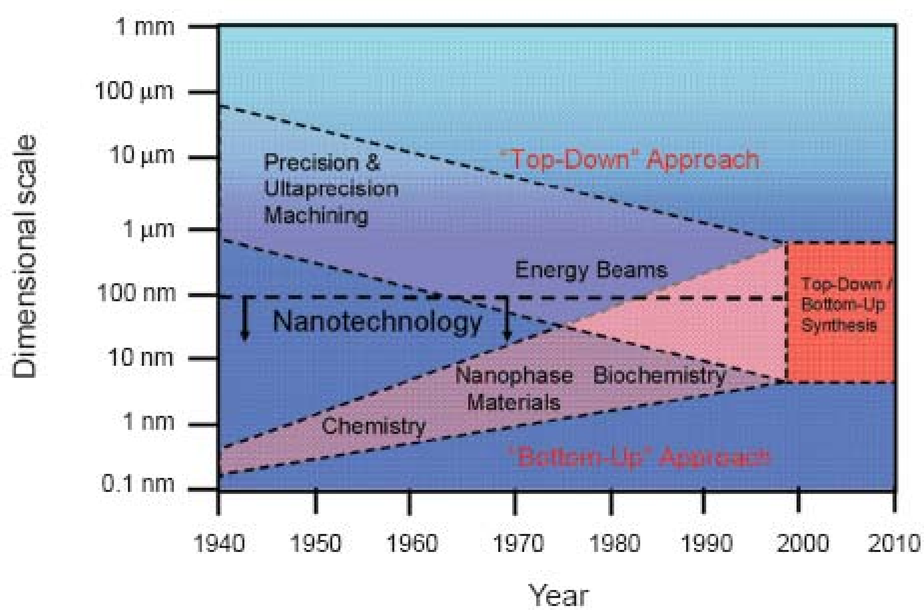


Figure A8.1 Illustration of Top-Down/Bottom-Up Nanotechnology Fabrication Synthesis (Whatmore, 2005, 73).

Molecular manufacturing is a hot topic in the nanotechnology community. It takes the bottom-up approach to the next level. Molecular manufacturing is the capability of building complex systems that consist of multiple components with

molecular precision using molecular machines, called “assemblers” (NRC, 2006, 99). These molecular assemblers are envisioned to self-replicate and precisely control the arrangement of atoms to inexpensively produce complex structures (Drexler, 2006, 2). This concept has been championed by Dr. K. Eric Drexler, a pioneer in the field of nanotechnology. Dr. Drexler writes, “Where chemists mix molecules in solution, allowing them to wander and bump together at random, molecular assemblers will instead position molecules, bringing them together in a specific position, orientation, and sequence” (Drexler, 2006, 2). Many in the science and technology community question the technical feasibility of these world-shattering ideas. However, whether molecular manufacturing is truly science or simply pseudoscience, the concept of building one atom at a time is part of the allure of nanotechnology.

APPENDIX 9: THE DETAILS OF MOORE'S LAW

It is important to understand the scaling trend known as Moore's Law to appreciate what is driving the current pace of change in the IT industry. Dr. Gordon E. Moore was the Director of Fairchild Semiconductor's Research and Development Laboratories when he published his, now famous, April 1965 article. Dr. Moore extrapolated early trends he observed in the silicon semiconductor industry to forecast the future development of integrated circuit (IC) technology. He wrote that the total number of components on an IC with the lowest manufacturing cost per component will double approximately every 12 months from 1965 to 1975 (Moore, 1965, 2). In a video interview for Intel Corporation, Dr. Moore acknowledged, "I had no idea this was going to be an accurate prediction, but amazingly enough instead of ten doubling[s], we got nine over the ten years, but still followed pretty well along the curve" (Intel, 2005, 1).

In a speech to the Institute for Electrical and Electronics Engineers International Electron Devices Meeting in 1975, Dr. Moore changed his original technology forecast, adjusting his projected exponential growth period from 12 months to 24 months. He stated, "The rate of increase of complexity can be expected to change slope in the next few years. . . . The new slope might approximate a doubling every two years, rather than every year, by the end of the decade" (Moore, 1975, 13). Dr. Moore's original calculations were based on the total number of components to include transistors and capacitors. The 1975 complexity calculation is based solely on the total number of transistors. This final principle was dubbed by computer scientist Dr. Carver Mead as "Moore's Law" (Intel, 2005, 1). **Moore's Law** states integrated semiconductor circuit density, or number of transistors on a chip, doubles every 24 months (IRC, 2005, 1).

These advances in silicon IC electronics form the foundation of the progress of information technology (IT). Figure A9.1 provides a graphical representation of Moore's Law from its origin in 1965 extrapolated out to 2031. As the world's largest chip maker, Intel Corporation's transistors per production chip listed in Table A9.1 has been plotted on Figure A9.1 to show how closely Moore's Law has tracked with reality.

Figure A9.1 Moore's Law (Extrapolated to 2031)

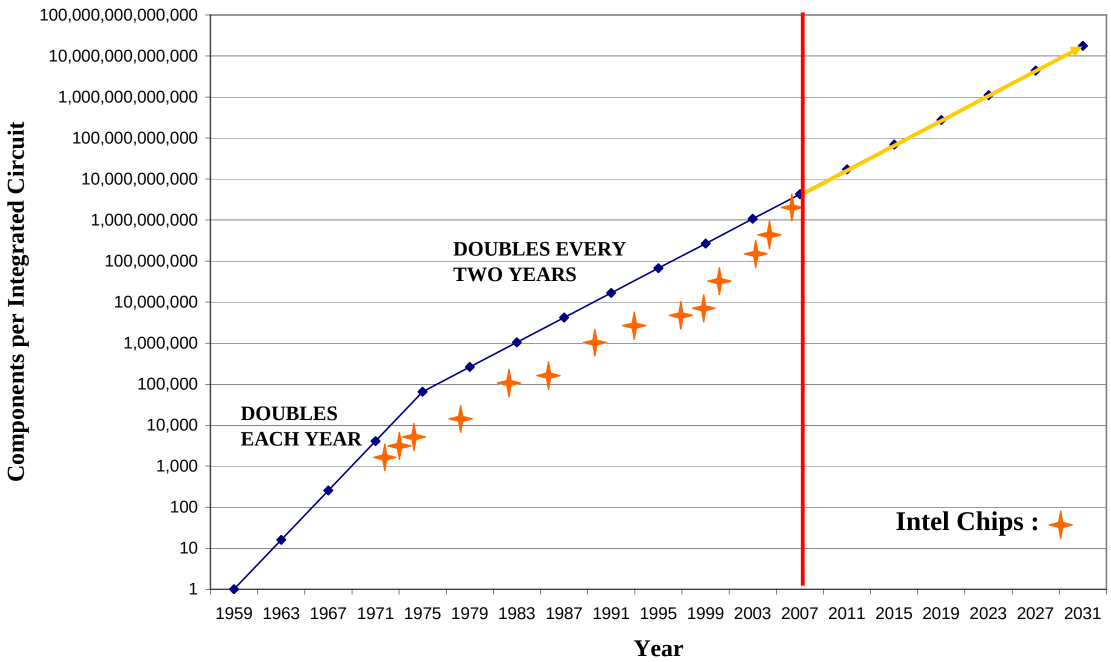


Table A9.1 Intel Corporation Transistor Counts

Year	Microprocessor	Transistors/Die
1971	Intel 4004	2,300
1972	Intel 8008	3,500
1974	Intel 8080	4,000
1978	Intel 8086	29,000
1982	Intel 286 Processor	134,000
1985	Intel 386 Processor	275,000
1989	Intel 486 Processor	1,200,000
1993	Intel Pentium Processor	3,100,000
1997	Intel Pentium II Processor	7,500,000
1999	Intel Pentium III Processor	9,500,000

2000	Intel Pentium 4 Processor	42,000,000
2003	Intel Itanium 2 Processor	220,000,000
2004	Intel Itanium 2 (9 MB Cache) Processor	592,000,000
2006	Intel Dual-Core Itanium 2 Processor	1,700,000,000

NOTE: Data compiled from Intel Corporation's website (http://www.intel.com).

For 42 years, the increasing computational density inherent in Moore's Law has been the driving force for the world-wide digital revolution. It has become shorthand for the rapid rate of technological progress. Scaling has been the organizing theory for the progress of the semiconductor industry over these past four decades. It has created a structure for continued process improvement in and helped integrate the entire industry around design and manufacturing. The impact of transistor miniaturization is improved performance, or computational speed, because electrons do not have to travel as far. The ability to pack more and more transistors and other circuitry onto chips has also steadily increased their functionality.

Moore's Law was never considered a law of physics, but rather a rule of thumb about how complex ICs would become. Bear in mind, this pace of transistor doubling is actually an average over longer periods of time. There is no smooth incremental ascent in the short term as innovations and discoveries that advance technology do not appear in a predictable fashion. The IT industry has adopted the trend in order to plan and focus its capital investments on key issues to promote the constant evolution of silicon semiconductor technology. Moore's Law is therefore often seen as a self-fulfilling prophesy made possible by the reinvestment of product profits toward the creation of even more creative and popular merchandise. "Instead of filling a market need, the

semiconductor industry has actively and aggressively created markets" (Tuomi, 2002, 30).

The interpretations and uses of Moore's Law have grown and propagated far beyond Dr. Moore's original intent. In his article "The Lives and Death of Moore's Law," Dr. Ilkka Tuomi writes that most published pieces that quote Moore's Law historically misrepresent or extend its scope far beyond existing evidence (Tuomi, 2002, 4). This famous computing principle has been applied to other computer growth trends such as hard-drive densities and number of hypertext markup language web pages. Dr. Moore has joked, 'Moore's Law has come to be applied to anything that changes exponentially, and I am happy to take credit for it" (Kanellos, 2005, 2). Dr. Moore emphatically says he never said 18 months for anything, which is the often-misquoted timeframe for Moore's Law.

Mr. David House, a former Intel Corporation executive, is the individual who extrapolated that the doubling of transistors doubles processor performance every 18 months. In truth, performance doubles closer to every 20 months (Kanellos, 2005, 2). Dr. House derived the 18 month timeframe by considering not only the exponential growth of chip complexity, but also increases in performance due to higher clock frequencies (Tuomi, 2002, 18). One panelist noted that historical improvements in clock speed are currently stalled because it is becoming so difficult to further miniaturize the silicon, field effect transistor.

The **end of Moore's Law** has been erroneously speculated many times over the past few decades. In 1978 and again in 1988, IBM scientists predicted Moore's Law had only 10 years left. Dr. Gordon Moore himself thought his law would end at the 250 nm

manufacturing process, a landmark the semiconductor industry passed in 1997 (Kanellos, 2005, 4). So how far can the transistor shrink? The only true boundaries to innovation are the absolute limits of physical science—quantum and thermal limitations of complexity. The regular doubling does mean that these absolute boundaries are approaching rapidly.

Moore's Law cannot continue forever. The continued increase in the number of transistors with the corresponding decrease in size is pushing the semiconductor industry toward the dimension of a single atom—.3 nm in diameter for silicon and .2 nm in diameter for carbon. This is the ultimate scaling limit since transistors and wires cannot be made smaller than an atom and solids cannot be produced out of hydrogen. Manufacturing process technology is now at the point where some features/structures inside chips, such as the gate oxide layers are already only a few atomic layers thick, and cannot shrink much further. In an April 2005 interview with Techworld, Dr. Moore stated, "We have another 10 to 20 years before we reach a fundamental limit" (Dubash, 2005, 1).

Semiconductor manufacturers face a variety of technical challenges at the nanoscale. Electrons tunnel through flimsy walls several atoms thick causing unwanted electric current leakage out of the circuit. The electricity routing through the IC also generates searing heat which is more and more difficult and expensive to control (Baker, 2005, 71). Circuit designers must continue to dissipate the heat buildup generated by transistors within a tiny, confined space more effectively. Another serious problem is the growing power consumption for high-performance logic chips. If increasing clock frequency and IC density trends continue, the power consumption of a high-performance

microprocessor (MPU) will reach 10 kilowatts within several years and the power density at the surface of this silicon chip could be as large as 1000 watts per square centimeter which is equivalent to the surface of a rocket nozzle (Iwai et al, 2005, 12). Additionally, power leakage becomes more problematic with shrinking feature sizes, wasting a higher portion of the total MPU power (Intel, 2006, 5). One panelist wrote, “We are far away from the fundamental size limits. . . . The real issue is power dissipation, due to subthreshold slope, which IS a fundamental limit of charge-based devices. Unless we come up with another switch . . . scaling WILL end.” The IC industry has a tradition of blowing past technical barriers. Several times when it appeared that physical limitations such as power consumption would slow or even halt the growing trends, the industry found ways around the barriers with continued innovation.

Moore’s Law is not just about the science, it is also about the economics—the minimum cost per transistor for the manufacturer and the related price per bit of a memory chip, or price per operation of a microprocessor, for the consumer. Cost reduction has been the largest driving force for downscaling. In an interview conducted to honor the 40th anniversary of Moore’s Law, Dr. Moore reflected, “I was trying . . . get across the idea that this was the way electronics was going to become cheap. . . . Make the yields go up and get the cost per transistors down dramatically” (Intel, 2005, 1). The average cost of a transistor was $5.52 in 1954. By 2004, the average cost was 191 billionths of a dollar, or 191 “nanodollars” (Kanellos, 2005, 3).

The basic assumption of the ITRS is that Moore's Law, although perhaps slowing down, still provides a good basis for predicting future developments in the semiconductor industry. The ITRS is known to be conservative in its projections. For example, the

2005 ITRS projects a three-year timing cycle for the dynamic random access memory (DRAM) product, which represents the leading-edge of stagger-contacted metal 1 (M1) half-pitch, despite the historical actual two-year technology cycle trend. It takes two technology cycles to reduce the DRAM feature scale by one half (IRC, 2005, 61-2). The 2005 ITRS projects a three-year technology cycle meaning the slowing of Moore's Law's rate of on-chip transistors (functionality) to doubling every three years rather than the historical two-year pace of change (IRC, 2005, 74). Table A9.2 uses the 2005 ITRS to present DRAM M1 half-pitch and MPU physical gate length data projections out to 2031. Figures A9.3 and A9.4 have been provided as a visual reference for this data using a standard and logarithmic feature size scale respectively.

Table A9.2 Technology Trend Data

Year of Production	M1 Half-Pitch (DRAM)	Physical Gate Length (MPU)
1995	350	350
1997	250	180
1999	180	90
2001	130	65
2004	90	37
2007	65	25
2010	45	18
2013	32	13
2016	22	9
2019	16	6
2022	11	4
2025	8	3
2028	6	2
2031	4	1

NOTE: Data derived from ITRS, 2005 Edition and 2006 Update.
ITRS targets have historically turned out to be conservative.

Figure A9.2 Product Technology Trends

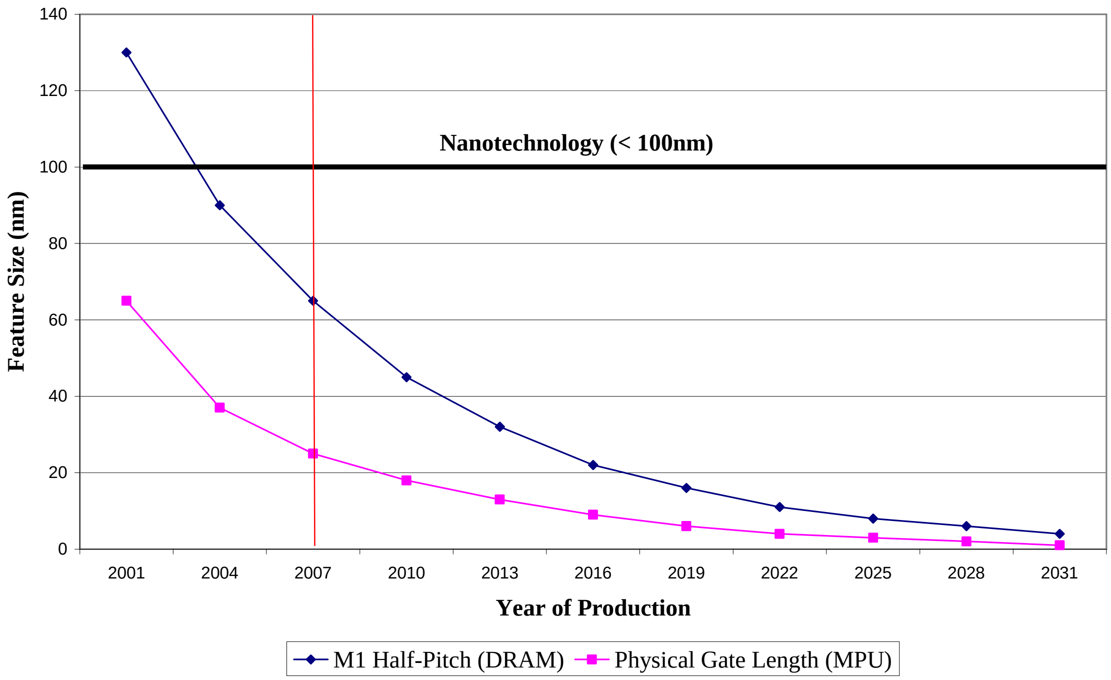
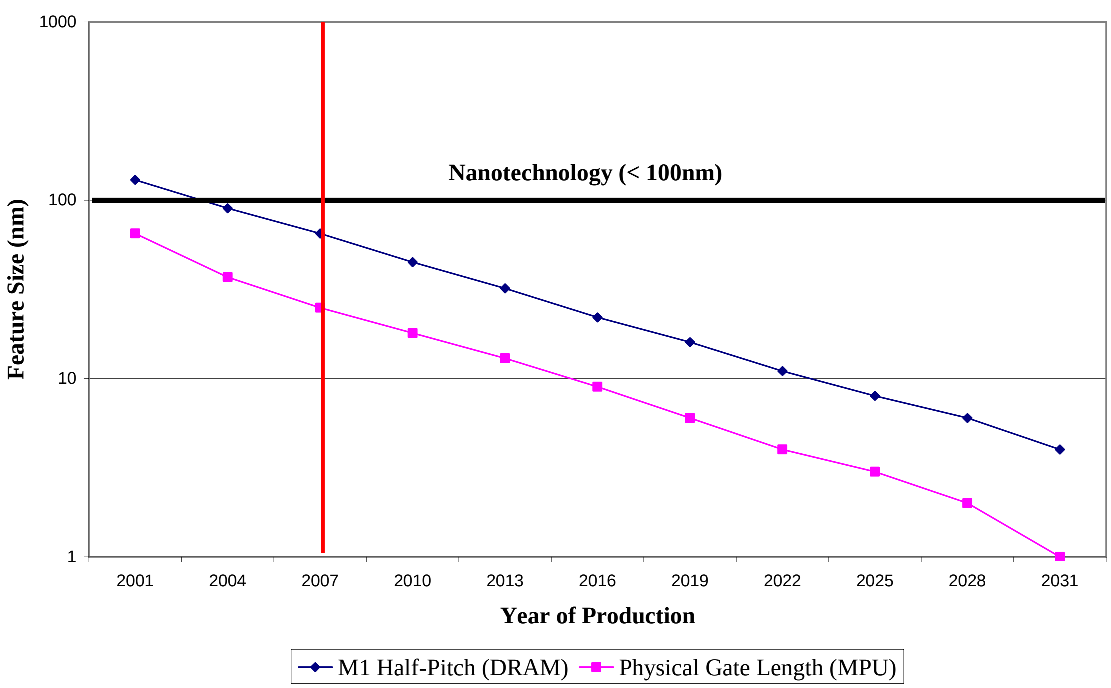


Figure A9.3 Product Technology Trends (Logarithmic)



APPENDIX 10: NANOTECHNOLOGY R&D BUDGET INFORMATION

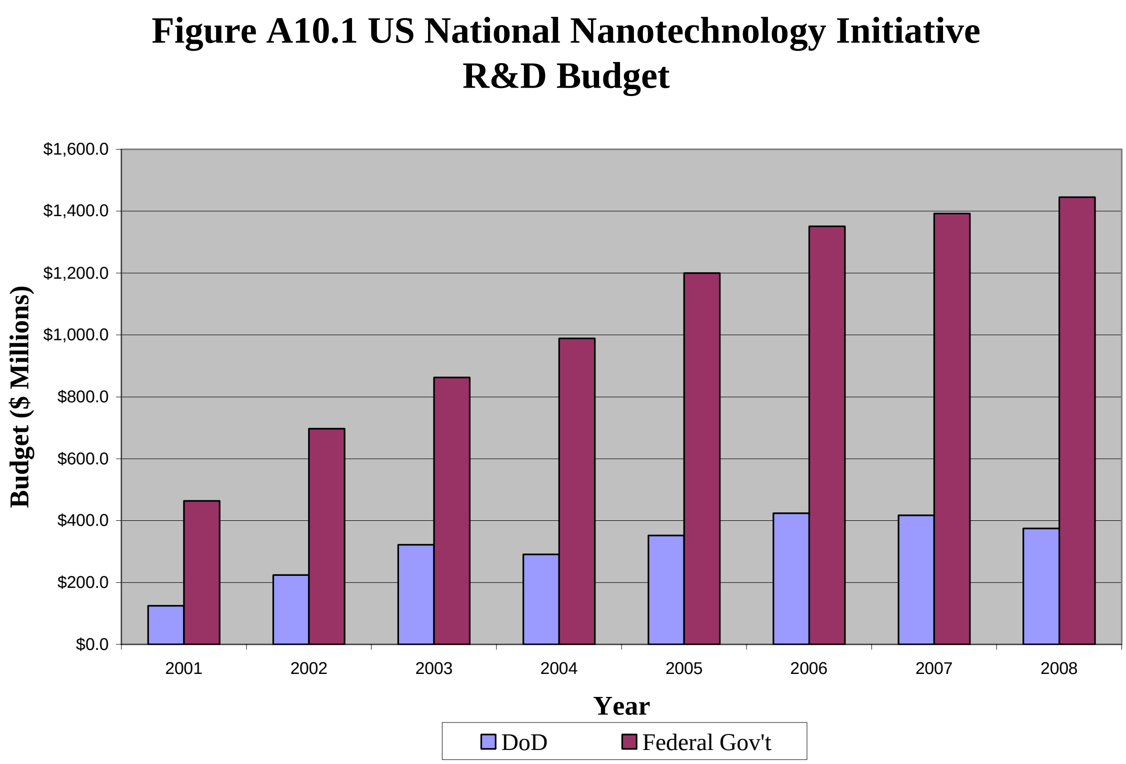


Table A10.1 US National Nanotechnology Initiative R&D Budget (Amounts in $M)

Year	DoD	Federal Gov't	Spending Value Type	Source of Data
2001	$125.0	$464.0	Actual	http://www.nano.gov/html/about/funding.html
2002	$224.0	$697.0	Actual	http://www.nano.gov/html/about/funding.html
2003	$322.0	$863.0	Actual	http://www.nano.gov/html/about/funding.html
2004	$291.0	$989.0	Actual	NNI President's 2006 Budget Supplement
2005	$352.0	$1,200.0	Actual	NNI President's 2007 Budget Supplement
2006	$423.9	$1,351.2	Actual	NNI President's 2008 Budget Supplement
2007	$417.2	$1,392.1	Estimated	NNI President's 2008 Budget Supplement
2008	$374.7	$1,444.8	Proposed	NNI President's 2008 Budget Supplement

Note: The US Federal Government budget numbers provided include the Defense Department (DoD) figures.

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APPENDIX 11: INFORMATION TECHNOLOGY AND NANOTECHNOLOGY BACKGROUND

A11.1. The Digital and Information Ages

The strategic significance of computers was recognized early by the US Government. The US Army produced Electronic Numerical Integrator and Computer (ENIAC), the world's first all-electronic computer, during World War II to improve the speed and accuracy of ballistics calculations. The ENIAC filled over 1800 square feet of floor space and required 174 kilowatts of power to operate causing brownouts in Philadelphia when the computer was turned on (Birnbaum, 2000, 1-2). Since ENIAC's activation in 1946, the capability and sophistication of computers has increased while the physical size of the components has decreased. Current cell phones are much more capable than ENIAC and consume far less power than a single one of its 17,468 vacuum tubes (Sargent, 2006, 135 and Birnbaum, 2000, 2).

From the beginning of all-electronic computation with ENIAC to the present, the **Digital Age** has stimulated a rapid, steady revolution toward smaller, more powerful and cheaper electronic components. This trend has enabled the paradigm shift from centralized to distributed processing capabilities such as personal computers. A similar progression toward larger capacity, easier access and lower cost data storage has occurred. Unlike processing and storage, display technology enhancements have progressed in significant, periodic jumps rather than steady, rapid strides.

Dr. Ilkka Tuomi, visiting scientist at the European Commission's Joint Research Centre, writes, "One of the important drivers for buying increasingly powerful computing equipment has been that new versions of operating system and application software have

typically demanded more processing power" (Tuomi, 2002, 29). Software, due to the progress of processors and storage, has become more user-friendly, flexible and capable with an increasing number, and variety, of application programs and programming languages. Further advances in IT device miniaturization and software promise even more pervasive distributed computing capabilities—often termed virtualization.

The US Defense Department's Advanced Research Projects Agency (ARPA)—today known as the Defense Advanced Research Projects Agency (DARPA)—in 1969 funded and developed an information communications network of interconnected computers called ARPA Network, or ARPANet (Hughes, 1998, 255). This data network eventually grew into the Internet and, along with it, sprung the **Information Age**. In contrast to computer enhancements, improvements in communication network capacity, known as bandwidth, have been relatively slow, but steady. However, rapid performance improvements in the communications technology continue to be anticipated to rival the pace of those seen by the computer industry.

The Information Age is all about the ability to rapidly process and interpret massive amounts of data. Global information communications and fast computation drive today's economic and social environment becoming an essential part of the modern way of life (Wilson et al, 2002, 191). Dr. Erich Ippen, professor of electrical engineering and physics at Massachusetts Institute of Technology, recently commented, "There hasn't been much economic pressure in the past couple of years to develop technology for [communications] applications because of the glut in bandwidth, but now communications demands are increasing again" (Bullis, 2007, 2). New computer applications on the horizon will necessitate higher bandwidth communications further

liberating computers to achieve their full potential. Sun Microsystems is known for the slogan: “the network is the computer.” Bandwidth has the potential to eventually become a substitute for computer processing.

The Internet has become a uniquely social medium for data sharing, knowledge management and mass collaboration demonstrating of the power of connectivity. The escalating value of a communications network as its size increases has been expressed as Metcalfe’s Law. This principle states the total value of a network to its users grows as the square of the number of users (Gilder, 1993, 3). This empirical description is named after Dr. Robert Metcalfe, co-inventor of the Ethernet network protocol. The validity of this principle, to include its shortfall of assigning equal value to all connections between individuals, is outside the scope of this paper. The point is the benefits of computer interconnectivity are only expected to increase due to the next-generation Internet, Internet2, and increased availability of personal computers.

An **integrated circuit (IC)** is the collection of interconnected transistors, diodes and circuits on a piece of semiconducting material—a silicon chip (BBC News, 2005, 2). The concept of miniaturizing the elements of an IC thereby achieving more functionality within the same surface area is referred to as scaling. Increased transistor density and reduced feature size for semiconductor electronics are the foundation of the great advances in information technology. This topic is discussed further detail in Section 2 and Appendix 9.

The term information technology and its acronym, IT, are heavily used in today’s computer-driven civilization but not always clearly understood. The Clinger-Cohen Act (CCA) of 1996 [40 U.S.C. 1401(3)], also known as the Information Technology

Management Reform Act, provides the following authoritative definition of **information technology**: "Any equipment or interconnected system or subsystem of equipment, that is used in the automatic acquisition, storage, manipulation, management, movement, control, display, switching, interchange, transmission, or reception of data or information . . . includes computers, ancillary equipment, software, firmware and similar procedures, services (including support services), and related resources" (US Congress, 1996, 27). IT has expanded in scope as it has matured from its core functions of processing, storage and communication to services such as security.

The future of computer and network technologies and their application are not always clear. Many authorities on the topic of IT have missed the mark with their technology forecasts. In 1943, Thomas Watson Sr., the founder of International Business Machines Corporation, said, "I think there's a world market for maybe five computers" (Bruce, 2003, 24). In 1977, Kenneth Olsen, the founder of Digital Equipment Corporation, said, "There is no reason why anyone would want a computer in their home" (Bruce, 2003, 24). In the October 11, 1994 issue of PC Magazine, Bill Gates, the founder of Microsoft Corporation, stated, "We'll have infinite bandwidth in a decade's time" (Gates, 1994, 79). Despite many uncertainties about the future of IT, the Digital and Information Ages show no signs of slowing down anytime soon. A recent RAND study titled "The Global Technology Revolution 2020, In-Depth Analysis" concluded that there is "no indication that the accelerated pace of technology development is abating, and neither is the trend toward multidisciplinarity nor the increasingly integrated nature of technology applications" (Silberglitt, 2006, xxvi).

The world of 2007 is far different than it was 23 years ago due in large part to the impact of IT. Over these past 23 years, personal computers and the Internet have become necessities in most every household. US society has become reliant on computers and the growing number of services they provide. In 2030, computing promises to be as different from what it is today as computing today is different from what it was in 1984. The next 23 years will no doubt see the many disruptive and discontinuous changes sparked by the transition from microelectronics to nanoelectronics—the current driving force in the field of nanotechnology.

A11.2. The Next Revolution—Nanotechnology

A **nanometer (nm)**, a metric unit of length equal to one-billionth (10^{-9}) of a meter, is the standard unit of measurement in the new field of nanotechnology. As a point of comparison, there are 25 million nm in an inch and a sheet of paper is about 100,000 nm thick (National Nanotechnology Initiative (NNI), 2006, np). Just think, National Basketball Association superstar Shaquelle O'Neal, at a height of seven feet, one inch, is 2.159 billion nm tall. Figure A5.1, a size reference graphic, has been provided in Appendix 5 to supply additional scale relationships to put this small dimension into proper context.

The origins of nanotechnology go back to December 1959 when Dr. Richard Feynman gave a landmark lecture titled “There’s Plenty of Room at the Bottom.” This talk to the American Physical Society meeting described a new field of physics with presumably “bottomless” possibilities—“the problem of manipulating and controlling things on a small scale” (Feynman, 1959, 2). Dr. Feynman highlighted the relevance of

this new field to the realm of computer technology. He stated, “Computing machines are very large; they fill rooms. Why can't we make them very small, make them of little wires, little elements---and by little, I mean *little*. For instance, the wires should be 10 or 100 atoms in diameter, and the circuits should be a few thousand angstroms across” (Feynman, 1959, 6). An angstrom is a unit of length equal to .1 nm, or 10^{-10} meters.

Dr. Norio Taniguchi is credited with first using the term “nanotechnology” in 1974 (Silberglitt, 2006, 155). Dr. K. Eric Drexler renewed enthusiasm for the field in his 1986 book, *Engines of Creation* (Schwartz, 2003, 167). There has been considerable debate over the proper meaning of this term; however, within the US, the NNI definition is commonly regarded as the authoritative description. Per the NNI, **nanotechnology** is defined as “the understanding and control of matter at dimensions of roughly 1 to 100 nanometers, where unique phenomena enable novel applications” (NNI, 2006, np).

Nanotechnology is a multi-disciplinary field that unites the various science and engineering groups to comprehend and direct nature at the atomic, or nanometer length scale. At the atomic level the old academic boundaries between biology, chemistry, physics and electronics lose much of their meaning as the sciences start to merge into a super-discipline (Baker, 2005, 70). The commercial semiconductor industry drove early nanotechnology research and development (R&D) efforts. This industry viewed nanometer length scale, or nanoscale, electronics as essential to making better products and also realized that new properties of materials were emerging at the nanoscale that they could harness (Saxl, 2005, 24). US military nanotechnology R&D began in the early 1980s with ultra-submicron electronics; by 1996, nanoscience was named one of six strategic research areas for defense (Altmann, 2004, 65). **Nanoscience** is “the study of

phenomena and manipulation of materials at atomic, molecular and macromolecular scales, where properties differ significantly from those at a larger scale" (The Royal Society, 2004, 2).

Nanotechnology works with the basic building blocks of nature—atoms and molecules—permitting an unprecedented degree of control over product production. There are two different philosophies on building matter at the nanoscale to a specification, "top-down" and "bottom-up." An overview of these two approaches has been included in Appendix 8. The appendix also contains information on molecular manufacturing, a controversial topic that has inspired considerable discussion on the true potential of nanotechnology.

Many applications of nanotechnology are based on the fact that common materials often display startling and useful new properties and phenomena at the nanoscale. Matter reduced to the molecular dimensions exhibits electrical, physical, optical and chemical properties that are not found in the respective bulk materials or molecules themselves. Breaking down a chuck of material into nanoparticles vastly increases its surface area to volume ratio, often by a factor of millions. This greater exposed surface area makes the material much more chemically reactive (Baker, 2005, 68). The larger surface area can also affect the strength and/or electrical properties of materials (The Royal Society, 2004, 2).

The curious rules/effects of quantum physics overrule the axioms of classical, Newtonian physics at the nanoscale. Dr. Feynman acknowledged this fact in his talk. He stated, "At the atomic level, we have new kinds of forces and new kinds of possibilities, new kinds of effects" (Feynman, 1959, 12). These quantum effects will influence the

electrical, optical and magnetic behaviors of materials (The Royal Society, 2004, 2). The crossover from classical to quantum physics is expected to occur when IC feature sizes get below 50 nm (Wilson et al, 2002, 205). In a quantum mechanical world, electrons are both discrete particles and waves—a paradox referred to as wave-particle duality (Sargent, 2006, 2). As a result, there is a mathematical limit on the accuracy with which it is possible to measure everything there is to know about a physical system. The more precisely the position of a particle is determined, the less precisely the momentum is known, and vice versa (Wilson et al, 2002, 206). This condition, known as the Heisenberg Uncertainty Principle, governs the observable nature of atoms and subatomic particles while its effect on measurements in the macroscopic world is negligible and usually ignored.

While there are a number of early nanoparticles, carbon nanotubes (CNT) are currently the most promising building blocks for future nanoscale technologies. CNTs are "tubes of carbon atoms less than one nanometer in diameter that emit light and conduct electrons one hundred times better than copper" (Motorola, 2006, 2) The CNT was discovered by NEC in Japan in 1991 (Baker, 2005, 70). These nanoparticles are "10 times stronger than steel but only 1/6th of the weight; they can be conductors or semiconductors, they possess an intrinsic superconductivity, are ideal thermal conductors and also behave as field emitters" (Saxl, 2005, 24). The excellent electronic properties of this versatile nanomaterial particularly make it attractive for use in future high-performance computers (Bullis, 2006, 2). Other building blocks of nanotechnology include buckyballs and quantum dots.

The impacts of nanotechnology on IT are anticipated to extend past improved scaling of ICs. As an example, computer display capabilities stand to benefit greatly from the material properties of nanoparticles. Liquid crystal display (LCD) computer monitors are rapidly replacing cathode-ray-tube (CRT) screens still prized for their excellent color rendition, wide viewing angles, and fast response time. Nanotechnology is now bringing these desired CRT-like features to the flat screen in the form of potentially less expensive, field-emission displays (Bullis, 2006, 1). Nanotechnology is also enabling ultra-thin and potentially flexible displays based on nanoscale semiconductor crystals called quantum dots. Theses would require much less energy than LCDs and feature more-vivid colors (Bullis, 2006, 1).

Nanotechnology also has the potential to revolutionize the Internet and communications. Transmitting data from one high-speed, fiber-optic (light-based) network to another currently involves passing through slower, electronic routers and switches. In 2004, Canadian researchers devised a new polymer material by manipulating buckyball nanoparticles, carbon atoms that look like soccer balls, to solve this “electronics bottleneck” on the Internet (Lovgren, 2004, 1). Such nanomaterials could be used to replace electronic switches with more efficient optical network switches enabling a rapid increase of the Internet's capacity. While today's electronic switches can perform ten billion operations per second, future optic switches may be able to relay a dizzying trillion operations per second (Lovgren, 2004, 2).

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APPENDIX 12: NANOTECHNOLOGY-IT IMPACTS AND THREATS TO USAF MISSION IN 2030

A12.1. Potential Technology Surprises

The US won't own all the clever nanotechnology ideas, and furthermore it won't bring most of them to market. One panel member wrote, "'Surprises' will occur from unanticipated exploratory areas, and the decreasing amount of curiosity-driven research in the US has a deleterious effect on being competitive in these areas." A technology surprise is a technological development that could undermine US military preeminence.

The US is at risk of attack on our computer and network infrastructure from nanotechnologies that we are unaware could exist. One panelist commented on this threat by writing, "The good news is that these nanotechnologies first appear as discovery concepts in the scientific community and then turn into technological uses. As long as the US remains engaged with the international nanoscience community, then the element of technological surprise from a nation state should be minimized." Another panel member wrote, "It is important to remain engaged with the international nanoscience community to avoid technological surprise from new discoveries, but it is also important for us to keep an eye to how to transition our own new discoveries to mature technologies (where highest priority impact is expected) more easily and quickly."

Table A12.1, located in Appendix 7, contains the collected panel inputs on the potential technology surprises from IT-focused nanotechnology in 2030. Many panel members anticipated that nanotechnology will create a new paradigm in military attacks and targets. These "new-wave" attack capabilities such as cyber attack, hardware viruses and worms may at some point place the whole US IT infrastructure in jeopardy. As an

example, our military information systems may be subject to stealthier cyber attacks. Some instantiations of this would be information coming from US satellites being disrupted, or our power systems being immobilized. The US could become much more vulnerable than we are today. As electronic control becomes pervasive the ability to corrupt that control will be an increasing risk factor. Computer virus and worm-based attacks could indeed cause major problems to existing and future weapons systems. While the US wants to use distributed information gathering and processing systems, our adversaries seek to exploit these systems and may deploy inherently stealth capabilities that form a distributed network which can attack our information networks or our energy grid, distribution systems.

Increased US military vulnerability to malicious threats such as “unreliable chips” (i.e., hidden Trojans) and other compromised components caused by growing overseas microelectronics outsourcing is a growing area of concern expressed among the panel. Globalization and the other economic forces generated by free markets and free trade continue to drive the development and production of some critical materials and parts for systems off-shore. Growing capital costs and changes in market demographics are shifting a large fraction of the IC business off-shore. In addition, US defense contractors can not afford to maintain low-volume foundries to supply chips to the US Department of Defense (DoD). These trends have led to a greater reliance by USAF, and the other services, on microchip fabrication outside of US government control. This situation has the potential to corruption of our sources of microelectronics. If the microchips in defense systems are compromised, the foundation of our national defense will be at risk. As the US military becomes more dependent on microchips, the DoD needs trusted IC

foundry capabilities within the US. The US government should also consider subsidizing US developers and suppliers to protect our position in IT.

A12.2. Threats Envisioned from Terrorists

Two facts have emerged from the current Global War on Terror—this is going to be a long, "Cold War-like" conflict and our adversaries are very technologically savvy. Contemporary terrorist groups have demonstrated tremendous ingenuity and interest in using modern technology in unconventional and unanticipated ways. As Dr Silberglitt points out, “Changes in technology, and the deployment of new technologies in society, can result in new vulnerabilities and targets for terrorist attack” (Silberglitt, 2006, 209). The ever-growing, global dependence on IT makes computer and communications systems an attractive target for terror. The US must actively assess how terrorists and other potential adversaries of tomorrow may maliciously apply IT-focused nanotechnologies to damage or destroy vital national interests.

The majority of panelists agree that it is highly probable that terrorists will use the combination of nanotechnology and IT against us in the future. One panelist wrote, “Our ignorance in understanding how terrorists will think to use nanotechnologies against us simply reflects our ignorance, not their ability to harness support for development and use of weaponized nanotechnologies.” IT-focused nanotechnology capabilities will be employed to recognize our military and societal vulnerabilities better and quicker than we do. The terrorists have already demonstrated that they can successfully use existing technical capabilities from the commercial marketplace to harm and kill Americans—whether they are airplanes or cell phones.

Table A12.2 contains the panels' judgments of IT-focused nanotechnology threats envisioned from terrorists. The panel settled on cyber attacks and small, autonomous vehicles as its two, foremost terrorist threats. Cyber attacks on critical, US computer-controlled infrastructure and other IT systems is well-suited to small groups of highly specialized experts like terrorist organizations. Cyber-terrorism threatens to undermine the IT applications and exploit infrastructure vulnerabilities. The US' dependence on IT will increase due to nanotechnology.

Nanotechnology-based autonomous vehicles for intelligence gathering and direct attack provide an inexpensive capability to asymmetrically attack the US and its interests, and obtain information from our forces without our knowledge. In 23 years, very cheap, commercially available technology will be easily and inconspicuously weaponized. One panelist proposed that terrorists could use widely available IT products, such as toy parts, to make a lot of small vehicles, like artificial rats or bats, programmed to infiltrate a wide variety of installations for either intelligence gathering or for direct terrorist activity, like releasing a toxin, et cetera. Terrorists might simply buy existing toys and modify them for their own use. A second panelist suggested terrorists could use thousands of programmable toy cars or planes modified to deliver explosives or pathogens to overwhelm the defenses of a critical installation. Also, a panelist noted that trying to defend against the threat of nanotechnology-based autonomous vehicles could be extremely expensive.